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Life Cycle Assessment of PVC-A polymer alloy pipes for the impacts reduction in the construction sector

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The plastics and construction sectors are at the heart of European policies for the circular economy. Polyvinyl chloride (PVC) is the most used polymer in construction products and one of the major applications is piping systems for water distribution. The PVC-A polymer alloy is made blending PVC with chlorinated polyethylene and it is characterized by improved physical properties that allow a reduction in pipe's thickness. These characteristics enable a reduction in the consumption of resources, but a comprehensive analysis of environmental performance is needed to identify any trade-offs. The aim of this work is to apply Life Cycle Assessment to evaluate two PVC-A piping systems with different gaskets. The study was conducted according to the EN 15804 standard and primary data from an industrial-scale production process were used. An extensive comparison with the main alternatives on the market (PVC-U, PVC-O, PVC-M, and PE) is reported, both referred to 1 kg and 1 meter of pipe.

1. Introduction

The European Circular Economy Action Plan has individuated plastics and construction sectors as key-value chains that require urgent, comprehensive, and coordinated actions (European Commission, 2020). In 2018, 20% of plastic production was for the construction sector. This percentage concerned the piping systems for which unplasticized PVC (PVC-U) is mainly used, while the adoption of PVC-alloy (PVC-A) is increasing.
The latter polymer is made from PVC-U and chlorinated polyethylene (CPE) which improves performance in terms of resistance to crack propagation, ductility, and resilience (Battaglin and Melotti, 2019). CPE acting as an impact-resistance modifier (Fitzpatrick et al., 1996), allows having the same mechanical performance as PVC-U with a 30% thickness reduction (Ferraiuolo et al., 2020).
Despite this advantageous physical and mechanical performance, no environmental analysis of PVC-A piping systems is available in the literature today.
Life Cycle Assessment (LCA), as defined by ISO 14040 (ISO, 2020a) and ISO 14044 (ISO, 2020b), is the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle.
For the construction sector, the use of Environmental Product Declarations (EPD) to communicate LCA results is widespread (Toniolo et al., 2019). In fact, the application of the European standard EN15804 (CEN, 2013) ensures the homogeneity in the methodological choices in the conduction of LCA.
EPDs of pressure piping systems made of PVC-U, PVC-O, PVC-M, and PE are currently available (EPD International AB, 2020).
The aim of this research is therefore to evaluate the potential environmental impacts associated with the production of PVC-A piping systems (according to EN15804) and compare the results with the main alternatives available on the market.

2. Methodology

The LCA methodology is an iterative process made of four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation of the results. The methodological choices adopted and the data used to conduct the study are introduced below, while the impact assessment results are presented and discussed in the next section.

2.1 Goal and Scope definition

The aim is to analyse the environmental performance of two different PVC-A piping systems. The difference between the two types of systems is the gasket they have: the first (hereinafter PVC-A PG) has a gasket made of plastic material (EPDM and PP) and glass fibre, while the second (PVC-A IG) possess a gasket made of ductile iron and EPDM. Thanks to the iron-based gasket, PVC-A IG can be installed in trenchless mode. The declared unit chosen for the study is 1 kg of piping system (including gasket). This choice allows to describe the specific impacts of each configuration regardless of nominal diameter (ND) and working pressure (NP) through the weights per meter.
The study system boundary is "from cradle to gate" and corresponds to modules A1, A2, and A3 of the EN 15804 standard. Therefore, the production and supply of raw materials are considered, as well as the production process of the pipe (Figure 1).

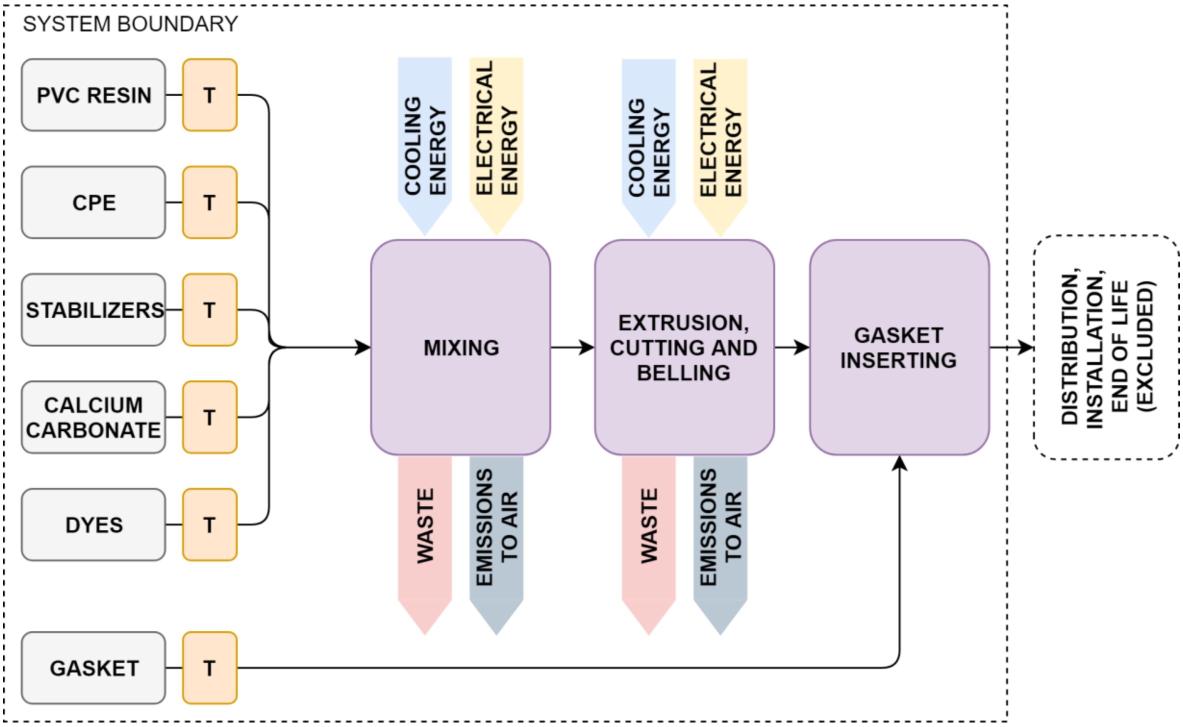

Figure 1: Production process and system boundary

The considered impact categories are Climate Change (CC), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Formation Potential (POCP), Abiotic Depletion Potential – Elements (ADPE), and Abiotic Depletion Potential – Fossil Resources (ADPF). The characterization factors used for the impact assessment are taken from CML-IA 4.1 (CEN, 2013). Moreover, the "Total Use of Non-Renewable Primary Energy Resources" (TNRE) indicator is also reported and discussed in this study. The model was created in SimaPro v9.0 environment (Pré Sustainabilty B.V., 2019).

2.2 Life Cycle Inventory Analysis

The study was conducted using primary data provided by a manufacturer located in north-eastern Italy. The data refer to the entire production of 2018. The primary data cover quantity of raw materials used, supply distance, quantity of packaging used, consumption of electricity and cooling energy, emissions into the air, and waste generated. For the characterization of raw materials, transport processes, and energy carriers, reference was made to Ecoinvent v3.5 (Wernet et al., 2016) and Industry Data v2.0 databases. The latter database was used for the characterization of the PVC resin through the eco-profiles made by PlasticEurope (PlasticsEurope, 2016). Table 1 shows the composition of the compounds and the datasets used for their modeling.

Table 1: Content declaration of 1 kg of piping system

Material	PVC-A PG	PVC-A IG	Dataset used
PVC Resin	87.9%	84.2%	Polyvinyl chloride, from suspension process, S-PVC, at plant/RER
CPE	5.8%	5.6%	Primary data-based modeling using: Polyethylene, low density, granulate {RoW}! Production | Cut-off, Chlorine, liquid {RoW}| chlorine production, liquid | Cut-off, U, Water, CN and Electricity, medium voltage {CN}| market group for | Cut-off, U
Calcium Based stabilizer	3.9%	3.7%	Data from (VITO 2016)
Calcium Carbonate	0.9%	0.9%	Calcium carbonate, precipitated {RER}| calcium carbonate production, precipitated | Cut-off, U
Dyes	1.0%	0.9%	Polyvinyl chloride, from suspension process, S-PVC, at plant/RER, Chemical, organic {GLO}| market for | Cut-off, U and Copper
Gasket	0.5%	4.8%	For PVC-A PG: Polypropylene, granulate {RER}| production | Cut-off, U, Injection moulding {RER}| processing | Cut-off, U, Glass fibre reinforced plastic, polyamide, injection moulded {RER}| production | Cut-off, U and Synthetic rubber {RER}| production | Cut-off, U; For PVC-A IG: Cast Iron {RoW} production | Cut-off, U and Synthetic rubber {RER}| production | Cut-off, U

The trigeneration plant of the production site was considered for modelling the energy vectors. Therefore, the consumption of resources for electric energy generation was modelled as a mix of grid energy absorption (using the Italian residual mix (AIB, 2018)) and natural gas utilization for self-power generation. Accordingly, cooling energy is provided from the trigeneration plant and it is distributed by the circulation of refrigerated water.
The raw materials, after being weighed, are sent to the mixing process. Afterwards, the mixture is cooled and undergoes extrusion, cooling, calibration, marking, cutting, and labelling processes. Lastly, the gasket is inserted, and the pipe is packed with wooden pallets (0.13 kg of wood per kg of pipe). The data on material and energy consumption for the listed operations are summarized in Table 2. The production waste is internally recycled Whereas, the contribution of internal handling, lighting, disposal of general waste, and water consumption, since they do not contribute significantly to environmental impact are omitted even if accounted.

Table 2: Inputs and outputs for the pipes production

Process	Input/Output	Units	Quantity	Process	Input/Output	Units	Quantity
Mixing	Raw Materials	kg	1039	Extrusion, cutting and belling	PVC-A	kg	1110
	Electrical Energy	kWh	65		Electrical Energy	kWh	317
	Cooling Energy Output	kWh	26		Cooling Energy Output	kWh	249
	PVC-A	kg	1000		Pipe	kg	1000
	Particulates to air	g	26		Particulates to air	g	4
	TOC to air	g	23		TOC to air	g	16
	Waste	kg	39		Waste	kg	110

2.3 Comparison with other materials

To make a comparison with other technological solutions on the market, a search was carried out on the website of the Program Operator "The International EPD® System" (EPD International AB, 2020). Four EPDs were identified from which the environmental impact profile of pipes made of PVC-U, PVC-O, PVC-M was derived (two data sets for each polymer). All studies were conducted using the same Product Category Rules (The International EPD® System, 2012) ensuring the homogeneity of the analysis and thus the validity of the

comparison The data used are shown in Table 3. For the comparison, the average of each polymer was considered and expressed about both 1 kg and 1 meter of pipe.
The ND 200 mm and NP 16 bar configuration was considered for the comparison with PVC pipes and the ND 200 mm and NP 10 bar configuration for the comparison with PE pipes.

Table 3: Environmental impact values for 1 kg of piping system extrapolated from the analysed EPDs. (1) (Iplex, 2017) *(2)* (Vinidex, 2017) *(3)* (Iplex, 2018) *(4)* (Vinidex, 2018)

Parameter	PVC-U (1)	PVC-U (2)	PVC-O (1)	PVC-O (2)	PVC-M (1)	PVC-M (2)	PE (3)	PE (4)
CC (kg CO_2 eq)	2.70E+0	2.68E+0	3.59E+0	3.71E+0	3.52E+0	3.50E+0	3.52E+0	3.47E+0
ODP (kg CFC_{11}eq)	1.03E-6	9.97E-7	4.65E-8	4.78E-8	4.69E-8	4.94E-8	3.68E-8	5.30E-8
AP (kg SO_2 eq)	8.05E-3	8.28E-3	9.62E-3	9.92E-3	9.56E-3	9.56E-3	9.49E-3	9.76E-3
EP (kg PO_4eq)	1.85E-3	1.93E-3	2.39E-3	2.50E-3	2.38E-3	2.38E-3	2.34E-3	2.41E-3
POCP (kg CH_4eq)	5.30E-4	5.63E-4	3.97E-4	3.80E-4	3.78E-4	4.16E-4	3.57E-4	4.25E-4
ADPE (kg Sb eq)	1.40E-6	1.48E-6	4.61E-6	4.78E-6	4.64E-6	4.66E-6	4.40E-6	4.79E-6
ADPF (MJ)	5.85E+1	5.73E+1	2.20E+1	2.38E+1	2.51E+1	2.38E+1	2.20E+1	2.62E+1
TNRE (MJ)	6.27E+1	6.14E+1	6.95E+1	7.24E+1	7.13E+1	7.11E+1	7.04E+1	7.27E+1

3. Results and Discussion

3.1 Life Cycle Impact Assessment

The characterized results of PVC-PG and PVC-A IG are reported, respectively, in Table 4 and Table 5. Environmental impacts are presented in percentage contributions of PVC, CPE, Gasket, Other Raw Materials (RM), Energy (electrical and cooling), Transport and Manufacturing.

Table 4: Life Cycle Impact Assessment for 1 kg of PVC-A PG

Parameter	Total	PVC	CPE	Gasket	Other RM	Energy	Transport	Manufacturing
CC (kg CO_2 eq)	2.70E+0	73.7%	4.5%	0.6%	4.5%	9.9%	5.0%	1.8%
ODP (kg CFC_{11}eq)	1.03E-6	89.8%	1.1%	0.1%	2.4%	4.0%	2.1%	0.6%
AP (kg SO_2 eq)	8.05E-3	54.2%	6.1%	0.7%	6.6%	15.5%	13.5%	3.4%
EP (kg PO_4eq)	1.85E-3	50.2%	6.0%	1.0%	10.1%	15.9%	12.8%	4.1%
POCP (kg CH_4eq)	5.30E-4	70.2%	4.3%	0.7%	5.1%	8.1%	6.3%	5.4%
ADPE (kg Sb eq)	1.40E-6	2.4%	7.5%	0.8%	40.1%	18.0%	22.7%	8.5%
ADPF (MJ)	5.85E+1	80.0%	4.7%	0.6%	3.5%	6.4%	3.3%	1.4%

Table 5: Life Cycle Impact Assessment for 1 kg of PVC-A IG

Parameter	Total	PVC	CPE	Gasket	Other RM	Energy	Transport	Manufacturing
CC (kg CO_2 eq)	2.68E+0	70.8%	4.3%	3.5%	4.4%	9.6%	5.5%	1.8%
ODP (kg CFC_{11}eq)	9.97E-7	89.0%	1.1%	0.5%	2.3%	4.0%	2.5%	0.6%
AP (kg SO_2 eq)	8.28E-3	50.4%	5.6%	4.8%	6.3%	14.4%	15.2%	3.3%
EP (kg PO_4eq)	1.93E-3	46.0%	5.5%	7.2%	9.5%	14.6%	13.3%	3.9%
POCP (kg CH_4eq)	5.63E-4	63.2%	3.9%	9.0%	4.7%	7.3%	6.9%	5.1%
ADPE (kg Sb eq)	1.48E-6	2.2%	6.8%	7.0%	36.5%	16.4%	23.1%	8.0%
ADPF (MJ)	5.73E+1	78.0%	4.6%	2.5%	3.5%	6.2%	3.7%	1.4%

The two products show similar environmental profiles, except for the higher contribution of the PVC-A IG Gasket in all impact categories.
PVC resin is the main contributor in all categories (up to almost 90%) except for ADPE. For this category, the greatest impacts derive from the materials used to produce stabilizers (mainly zeolite). Other significant contributions in this category are CPE production (consumption of chlorine), transports (lead to produce lorries), and cooling energy (metals used to make the chiller). CPE, which differentiates PVC-A from other PVC alloys, shows the greatest impacts (always below 7.5%) in AP and EP, in both cases related to the raw material used. The PVC-A IG ductile iron gasket has impacts up to 9%, in particular in the categories POCP (due to the extraction and processing of iron), EP (combustion of Coke), and ADPE (production of EPDM).

3.2 Results of comparison

The results of the comparison referred to 1 kg of piping system are shown in Figure 2. The PVC-A shows better results compared with the other polymeric alloys. The categories CC, AP, EP, ADPE, and TNRE highlight the better environmental performance of PVC-A. On the other hand, the results in the ODP, POCP, and ADPF impact categories are worse for PVC-A than other polymeric solutions, other than PE, which shows lower impacts in the EP category but higher impacts in ADPF.

The major differences are found in the ODP, ADPE, and ADPF categories. The difference for the ODP category is due to the use of different datasets for the characterization of PVC. In fact, the dataset of the Industry Data library (used for PVC) attributes to the production process of PVC an emission of CCl_4 into the air about five hundred times greater respect the Ecoinvent v3.5 database. There are no other significant differences between the two datasets. For the ADPE category, the variations are due to the different compositions of stabilizers and dyes. The differences in the ADPF category can only be derived from different modeling, as the results for PVC-U, PVC-O and PVC-M contrast with what was reported for the TNRE indicator.

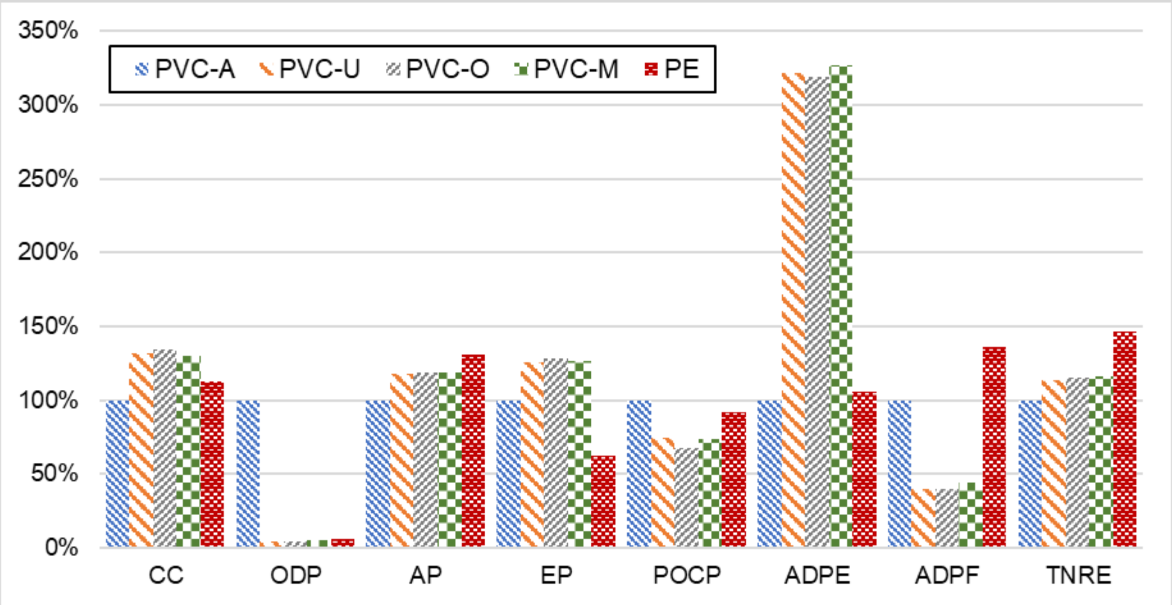

Figure 2: Comparison between 1 kg of different piping systems

The results expressed in terms of 1 meter of piping system highlight, even more, the reduction of the impacts of PVC-A, as it is lighter (with the same ND and NP) than other technological solutions with the exception of PVC-O (Table 6).

Table 6: Comparison between 1 m of different piping systems (ND 200mm). The absolute values and the percentage variation with respect to PVC-A are reported

Parameter	PVC-A (PN16)	PVC-U (PN16)	Var%	PVC-O (PN16)	Var%	PVC-M (PN16)	Var%	PVC-A (PN10)	PE (PN10)	Var%
Weight (kg/m)	7.99E-1	1.32E+0	+65%	6.97E-1	-13%	1.10E+0	+38%	5.30E-1	7.19E-1	+36%
CC (kg CO_2 eq)	2.15E+0	4.68E+0	+118%	2.52E+0	+17%	3.85E+0	+79%	1.42E+0	2.17E+0	+53%
ODP (kg CFC_{11}eq)	8.10E-7	6.33E-8	-92%	2.95E-8	-96%	5.49E-8	-93%	5.37E-7	4.17E-8	-92%
AP (kg SO_2 eq)	6.53E-3	1.27E-2	+94%	6.77E-3	+4%	1.06E-2	+63%	4.32E-3	7.69E-3	+78%
EP (kg PO_4eq)	1.51E-3	3.15E-3	+108%	1.69E-3	+12%	2.63E-3	+74%	1.00E-3	8.52E-4	-15%
POCP (kg CH_4eq)	4.37E-4	5.36E-4	+23%	2.57E-4	-41%	4.41E-4	+1%	2.90E-4	3.62E-4	+25%
ADPE (kg Sb eq)	1.15E-6	6.12E-6	+431%	3.20E-6	+178%	5.18E-6	+350%	7.63E-7	1.09E-6	+43%
ADPF (MJ)	4.63E+1	3.02E+1	-35%	1.60E+1	-65%	2.82E+1	-39%	3.06E+1	5.64E+1	+84%
TNRE (MJ)	4.96E+1	9.28E+1	+87%	4.98E+1	+0%	7.92E+1	+60%	3.29E+1	6.54E+1	+99%

4. Conclusions

This research presented an in-depth analysis of the environmental performance of PVC-A piping systems, providing an extensive comparison with the main alternatives on the market. PVC-A shows significant reductions in impacts in five out of eight categories in the comparison based on one kilogram of pipe. This trend is highlighted by moving the analysis to one meter of pipe, where PVC-A has an advantage thanks to its reduced weight. Future research developments could concern the extension of the system boundaries which might show further improvements related to transport (due to the lower weight) and installation (thanks to the trenchless installation made possible by the ductile iron gasket system) phases.

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