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ENVIRONMENTAL IMPACTS QUANTIFICATION OF PVC PRODUCTION

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Abstract

Due to the increasing and hazardous level of plastic pollution in our planet, many researchers and experts from the public and private sector have been working in order to promote and implement solutions overcoming this global issue.
The present project joins the scientific community in this discussion by focusing on polyvinyl chloride (PVC), which is considered one of the most used polymers in engineering infrastructures. The goal of the paper is to quantitatively assess environmental impacts of the PVC production with the aim of proposing cleaner industrial solutions and more environmentally sound products.
To this end, a Life Cycle Assessment analysis was used to evaluate the environmental performance of the PVC manufacturing process. The functional unit considered was 1 kg of PVC granules. The modelling was facilitated by the Gabi software developed with three different characterization methods: CML 2001, EDIP 2003 and ReCipe 1.08. Fossil fuels depletion, climate change and human toxicity resulted to be the most significant impact categories due, respectively, to the huge quantity of crude oil extracted, the big amount of emission released into the atmosphere and the intensive toxic substances involved during the whole process.
In the last section, a number of recycling and raw material alternatives were suggested to reduce the environmental impact obtained from the analysis.

Key words: Life Cycle Assessment, Polyvinyl Chloride, PVC granules, PVC recycling

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1. Introduction

Plastic is a family of different materials. It is divided between thermoplastic that can be melted and hardened depending if it is heated or cooled and thermoset plastic that changes chemically while heated and it cannot return to its original form once melted (Plastics Europe, 2019). Polyvinyl Chloride (PVC) is a thermoplastic and it represents the third most used polymer after polyethylene and polypropylene (Elashmawi et al., 2017; Prieto et al., 2016; Rangaswamy et al., 2018). Combined with some additives, it is one of the most versatile thermoplastic polymers (Pita et al., 2002).

In 2018 the plastic production reached 359 million tons worldwide (Peng et al., 2020; PlasticEurope, 2019). This number is expected to double in the next two decades and almost quadruple by 2050 (EMAF, 2016; Samani and Meer, 2019; Venkatachalam, 2018). Out of this total amount, 61.8 million tons are produced in Europe alone, which counts for 17% of the global production (PlasticEurope, 2019). The European plastic converters demand in 2018 was 51.2 million tons, of

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which packaging and building & construction represent the main sectors. In particular, PVC constitutes 10% of the total European amount mainly for building and construction activities (Plastics Europe, 2019) and its global production also increases by 3.2% every year (CR, 2014; Peng et al., 2020).

The PVC industry is surely a significant sector since it is involved in several applications: health and safety (it is broadly used in the medical sectors); pipes construction in order to supply clean water; packaging applications; survival equipment (such as life jackets); food packaging; children's toys; bottles; cables (ECVM et al., 2000; Liu et al., 2020). It is also an important socio-economic sector since it creates multiple jobs and opportunities with remarkable incomes (ECVM et al., 2000). In Europe it comprises over 21.000 companies, creating more than 530.000 new jobs with a final turnover higher than 72 billion euros (CEC, 2000).

More specifically, in commercial terms, PVC is a widely used polymer and it is applied in both forms: rigid and flexible (Fig. 1). The first is mainly used for pipes constructions, profile applications (windows and doors), packaging, cards, while the latter is obtained by means of plasticizers and mostly used in plumbing and rubber substitution (Khaleghi et al., 2017; McKeen, 2012; Peng et al., 2020).

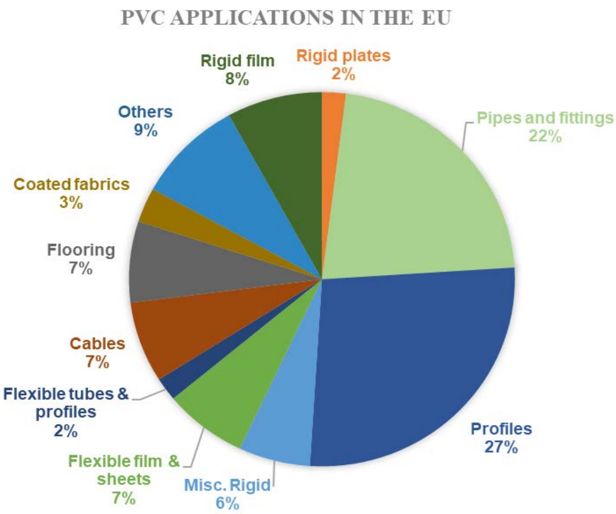

Fig. 1 PVC applications in Europe (Adapted upon ECVM, 2017)

The huge amount of PVC use leads to a large waste generation that needs to be monitored and analyzed in detail to improve end-of-life solutions (Mohammed, 2019). The challenge, hence, is to extend and turn the PVC industry into a sustainable sector. The European PVC industry keeps researching sustainability and circular economy-related projects by working on two parallel goals: to assess and improve the present situation and to develop sustainable commitments for future scenarios (ECVM et al., 2000). Moreover, the scientific communities and the private sectors are also developing overcoming solutions to reduce the polluting character of the PVC process industry (Falcke et al., 2017).

Among many, this section explores the work performed by VinylPlus, which is the 10 years Voluntary Commitment of European PVC industry towards a sustainable development (Vinyl Plus, 2017). The initiative is addressed to different scopes: reducing and/or minimizing the environmental impact during the production, promoting correct and fair use of additives, supporting waste collection and recycling alternatives, and encouraging discussion and dialogue among the PVC industry's stakeholders and decision-makers.

Given the peculiar nature of PVC, VinylPlus thereby suggests that we should dive deeper into innovative recycling alternatives for this specific type of plastic. Studies have also proven that depending on its applications, PVC can be recycled several times as, during the recycling process, the molecular chain length does not decrease (Vinyl Plus, 2017). This characteristic enables the recycled PVC to perform as well as virgin PVC.

Currently, two main methods are used for PVC recycling: mechanical recycling and feedstock recycling. Mechanical recycling is the process through which no polymer chains are broken down into smaller particles but rather, the components are mechanically separated and sorted into smaller fractions. It is divided into two categories: conventional and non-conventional technologies. The conventional technologies consist of sorting, shredding, and separating particles to obtain in the end a pulverized/granulated recycled PVC; on the other hand, non-conventional technologies make use of solvent-based processes and it generally suits better more complicated waste streams. The other option is feedstock recycling. The feedstock recycling process consists of the thermal treatment of the PVC waste and in most cases the hydrogen chloride is recovered and it can be sent back to the PVC production or it can be used in other applications (Vinyl Plus, 2020).

In 2019 VinylPlus reached 771,313 tonnes of PVC waste recycled, 4.3 % more compared to 2018, saving 1.5 million tonnes of CO_2 (VinylPlus Report, 2020). Within the EU Circular Plastic Alliance (CPA), VinylPlus committed to boosting its recycling rate up to 900,000 tonnes of PVC by 2025 and to at least one million tonnes by 2030 (VinylPlus Report, 2020).

Many research projects demonstrated the excellent performance of PVC recycling and the related environmental benefits. For instance, previous LCA-based studies have proved the importance of replacing raw materials to reduce potential PVC environmental impacts (Comanita et al., 2015; PlasticEurope, 2008). More specifically, according to Alsabri et al. (2020), in the piping industry, a switch to recycled polyvinyl chloride can reduce the climate impact from 36.21% to 15.53% for the production of 1 ton of polyvinyl chloride. Whereas, by analyzing the life cycle of PVC windows frame on both post-industrial and post-consumer waste, it was demonstrated that replacing virgin PVC with PVC from post – consumer waste saves around 2 tons of CO_2 eq./t while replacing virgin PVC from post-industrial waste saves around 1.8 tonnes of CO_2 eq./t (Stichnothe and Azapagic, 2012).

This study joins the scientific community by analyzing, specifically, the full life cycle of the PVC industrial life. The paper is divided into different sections: it starts with an extended overview of the PVC characterization and industry together with an LCA approach model in the materials and methods sections. The results of the assessment are then discussed. Finally, a review of current and more sustainable alternatives is reported.

2. Material and methods

2.1. PVC characterization

PVC is a chlorinated hydrocarbon polymer. The carbon atoms in the main chains are alternatively linked to hydrogen atoms and chlorine atoms. PVC is the result of the chemical polymerization of the vinyl chloride during which the double bond molecule is broken down to form a longer chain polymer (Fig. 2, Boustead, 2005). The production of PVC involves three main stages: the upstream of the PVC industry, the PVC industry, and the downstream of the PVC industry (Fig. 3).

The raw materials for the production of PVC are ethylene and chlorine, which are supplied upstream by the petrochemical industry (for ethylene) and the soda industry (for chlorine) (Pascault et al., 2012). The petrochemical industry produces ethylene through thermal cracking of naphtha, while the soda industry generates caustic soda, chlorine, and hydrogen thanks to electrolysis. Using ethylene and chlorine the PVC industry is able to manufacture an intermediate material called EDC which will thermally be cracked into VCM that eventually is polymerized to obtain PVC. In the downstream industry, PVC is mixed with several additives, stabilizers, and plasticizers (VEC, 2008).

Additives are necessary to guarantee specific properties to the final PVC product and they vary according to the intended application. Stabilisers are the ones that need to be assessed more carefully due to their hazardous features and, thus, their potential dangerousness for human health. They are added to help the PVC polymer not to degrade (Guangbao, 2020). The most used ones are lead stabilizers and cadmium stabilizers (CEC, 2000). On the other hand, plasticisers are added in order to obtain flexibility and workability in PVC products (Pereira et al., 2019). Also, in this case, the quantities of the plasticisers change according to the desired properties and the final use (CEC, 2000).

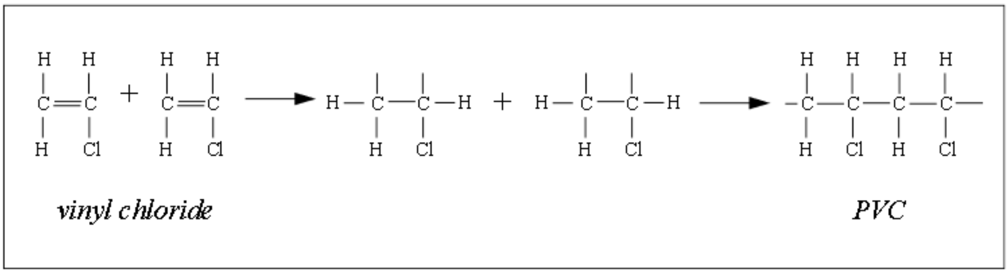

Fig. 2. Schematic representation of the polymerization of vinyl chloride (Boustead, 2005)

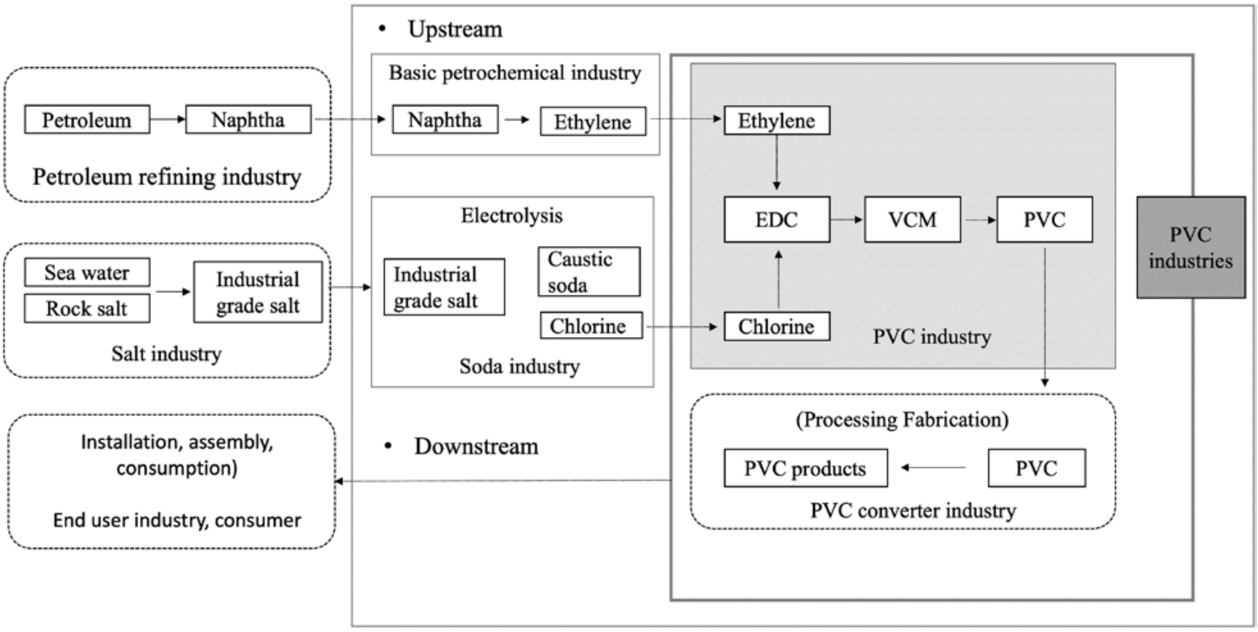

Fig. 3. Linkage of PVC related industries (Adapted upon VEC, 2008)

2.2. Methodology

The methodology adopted in this study is Life Cycle Assessment (LCA), which is an iterative tool able to identify possible environmental impacts associated with products and/or services (ISO 14040, 2006). According to the ISO 14040/44 four iterative stages are necessary in order to perform a valid LCA (ISO 14040, 2006; ISO 14044, 2006; Megange et al., 2020), as shown in Fig. 4.

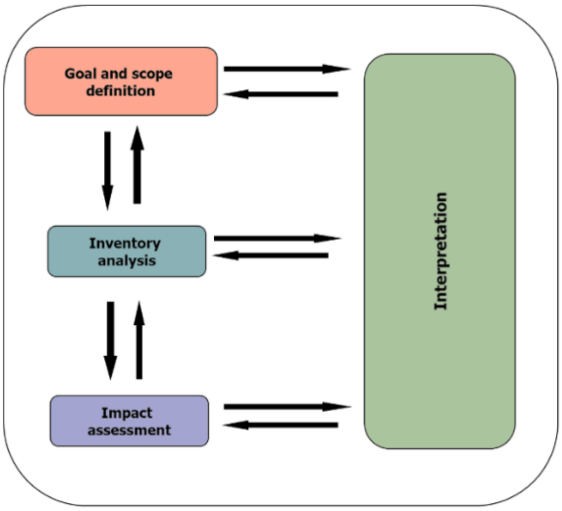

Fig. 4. Framework of LCA modified from the ISO 14040 standard (Hauschild et al., 2018)

2.3. Goal and scope definition

LCA has been performed in order to develop a quantitative analysis of the environmental impacts generated during the life cycle of a PVC product. The functional unit is 1 kg of Polyvinyl Chloride granules (raw material which eventually will be processed into final products). Data included in the study were gathered from literature and adapted to 1 kg of PVC considered (Boustead, 2005; Comanita et al., 2015; Ghinea, 2015; PlasticsEurope 2018). Additionally, missing data have been found in the Gabi database according to the purpose of the study.

The analysis focuses on the boundaries *cradle to gate* including all the stages from the raw materials extraction up to the end of the manufacturing industry. All the phases concerning the distribution, the use and the end of life have not been taken into consideration as they are not particularly relevant for the scope of the analysis. The methodologies chosen to run the LCIA are: ReCipe 1.08, EDIP 2003 and CML 2001. The results obtained are presented in normalized values-EU 25+3.

2.4. Life Cycle Inventory (LCI)

The inventory model is a crucial step in the LCA analysis as it links all unit processes involved in the study until the final product (Hauschild et al., 2018). This phase aims to collect all necessary quantities to develop product/waste flows and elementary flows dividing them between inputs and outputs within the system boundaries selected (Fig. 5). The inputs consist of the materials, energy and resources that enter into the unit process, whereas the outputs are represented by the products, waste and emissions resulting from the process (Hauschild et al., 2018). The inventory model of the analyzed PVC production has been developed dividing the system in three main stages of the life cycle process. Table 1 represents the LCI referred to 1 kg of polyvinyl chloride from suspension polymerization (S-PVC).

Particularly, a foreground system (consisting of the dataset strictly related to the study analyzed) are literature data adapted to the study purposes (Boustead, 2005; Comanita et al., 2016b; PlasticsEurope, 2019). Whereas, the background dataset consists of secondary data gathered in the Gabi software.

Table. 1. Life Cycle Inventory

I STEP: Ethane (C2H4) and Chlorine (Cl2) Production	
Input	***[kg]***
Petroleum	53.7
Salt (NaCl)	0.0015
Output	[kg]
Dioxins	0.0044
Particulates < 10µm	0.0035
Chlorides suspension	0.0003
NMVOC	0.0022
NaOH	0.0025
Cl_2 (chlorine)	0.0088
C_2H_4 (ethane)	0.9538
II STEP: VCM production process	
Input	***[kg]***
C_2H_4 (ethane)	0.9538
Cl_2	0.0088
H2	0.0783
$CuCl_2$	0.0044
O_2	0.0074
EDC impure	0.0845
EDC pure	0.3978
HCl	0.0349

Bentonite	0.0492
Distillation water	1.0280
Organic peroxides	0.0197
VCM impure	0.0857
VCM pure	0.0893
Output Materials	***[kg]***
Chlorinated hydrocarbons	0.0024
CO	0.0025
CO_2	0.0146
Waste water	0.631
NMVOC	0.001
NOx	0.0001
Energy released in the exothermal process - Output	**[kJ]**
Energy	0.027
III STEP: PVC production process	
Input Materials	***[kg]***
VCM pure	0.0893
Phenol	0.0013
Ca stabilizer	0.0023
Hydroxide	0.0002
Methylamine	0.0298
1,4-Butanediol	0.0023
2-methyl-2-butene	0.0027
Water	2.2390
Energy - Input	**[kJ]**
Energy	0.1509
Output Materials	***[kg]***
NMVOC	0.0016
Waste water	1.8328
PAH	0.0239
COD	0.0024
TOC	0.0073
Particulates < 10 ppm	0.003
PVC susp. from polymerization	1.0359
PVC from omogenization	1.9380
PVC from centrifugation	1.8370
PVC from washing	2.8390
Pure PVC from drying	1.0000

2.5. Life Cycle Impact Assessment (LCIA)

The third phase of the LCA is the Life Cycle Impact Assessment, during which the elementary flow resulting from the LCI are translated into environmental impacts (Hauschild et al., 2018). According to the ISO 14040, (2006) and ISO 14044 (2006) three steps are mandatory in a LCA analysis: the selection of a characterization model, the classification step and the characterization. As far as the first step is concerned, different characterization methods exist and they generally consist of two approaches: the problem-oriented approach called *mid – point* and the damage-oriented approach called *end-point*.

This study considers three different methodologies in order to propose a comparison between the results obtained. The characterization models chosen are: ReCiPe 1.08 (end-point), EDIP 2003 (mid-point) and CML 2001 (mid-point).

The indicators considered from the **ReCiPe 1.08** model are: *agricultural land occupation (ALO), climate change ecosystem (CCE), climate change human health (CCHH), fossil depletion (FD), freshwater ecotoxicity (FEc), freshwater eutrophication (Feu), human toxicity (HT), marine ecotoxicity (ME), metal depletion (MD), natural land transformation (NLT), ozone depletion (OD), particulate matter formation (PMF), photochemical oxidant formation (POF), terrestrial acidification (TA), terrestrial ecotoxicity (TE), urban land occupation (ULO).*

The second impact assessment methodology applied is **EDIP 2003**, which covers the following indicators: *acidification potential (AP), global warming (GW), photochemical ozone formation (POF) with impacts both on human health and vegetation, terrestrial eutrophication (TE) and aquatic eutrophication (AE)*

The last characterization model chosen is **CML 2001**, which focuses on the following impact categories: *Abiotic Depletion (ADP), Abiotic Depletion (ADP fossil), Acidification Potential (AP), Eutrophication Potential (EP), Freshwater Aquatic Ecotoxicity Pot. (FAETP), Global Warming Potential (GWP), Human Toxicity Potential (HTP), Marine Aquatic Ecotoxicity Pot. (MAETP), Ozone Layer Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), Terrestrial Ecotoxicity Potential (TETP).*

3. Results and discussion

This section will, firstly, describe the results obtained through the three different methodologies and, then, it will give a little discussion over the PVC industry by suggesting potential solutions for its polluting nature.

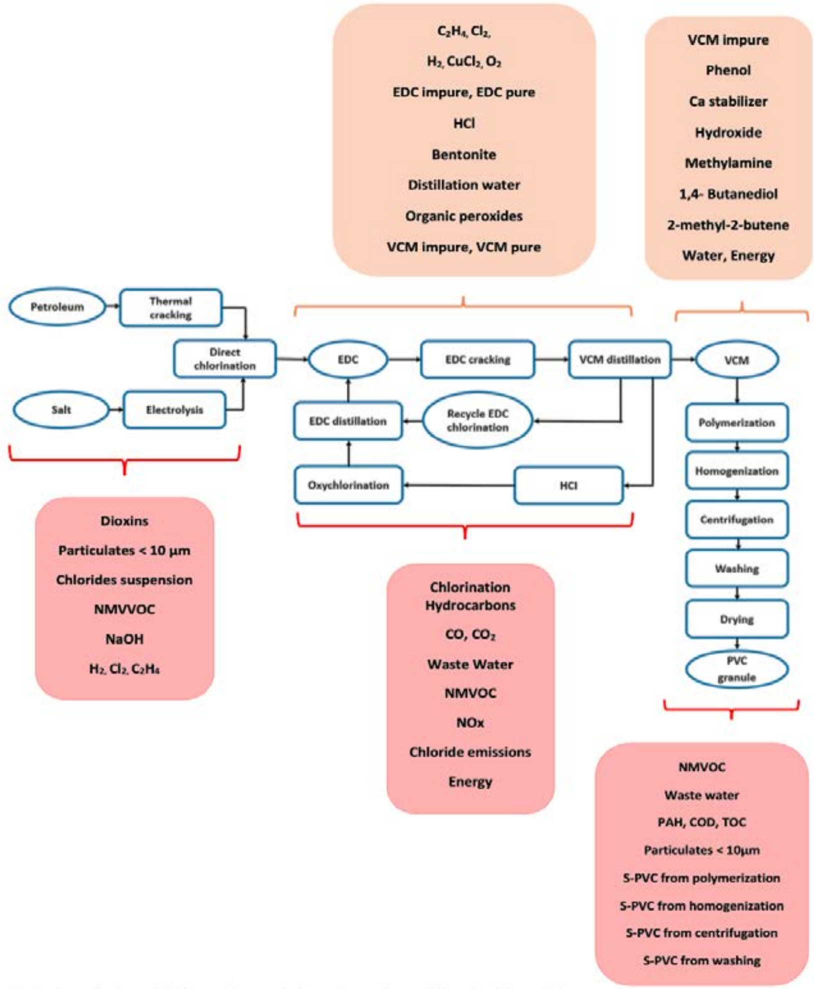

Fig. 5. Life cycle inventory (adapted upon Comanita et al., 2016a)

3.1. Environmental impact assessment with ReCiPe 1.08 methodology

The main environmental impacts resulting from the ReCiPe 1.08 methodology are shown in Fig.6, which are expressed in equivalent per person. The four categories are represented by a positive value, which means that they generate negative impacts on the environment.

According to the obtained results, *Fossil Depletion* (FD) shows the highest environmental impact, which is likely due to the large amount of crude oil extracted for the production of 1 kg of PVC; the second relevant impact category *Human Toxicity* (HT) is caused by the significant amount of hazardous and toxic substances used during the PVC processing production. The third biggest contribution is given by Climate Change. ReCiPe, in particular, considers human health damage (CCH) and loss of species (CCE): the characterization factor of human health damage is expressed in DALY, while the loss of species is calculated in Potential Disappeared Fraction of species (PDF) (ILCD Handbook, 2010a). Regarding the impacts generated by the consumption of chemicals, it was found that NO_2 and NO emissions are generated as a result of the use of catalysts for obtaining ethene. This leads to negative impacts associated with climate change, damaging both the ecosystem and human health.

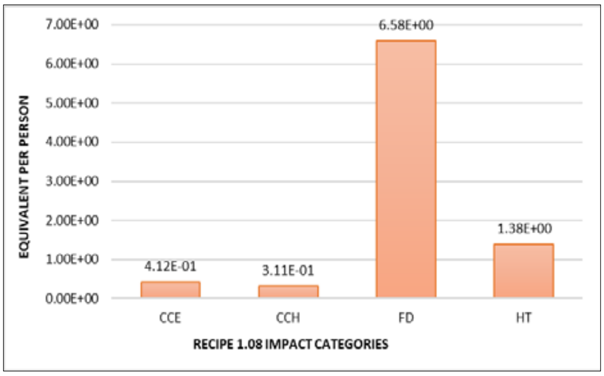

Fig. 6. ReCiPe 1.08 methodology - environmental impacts of PVC production

3.2. Environmental impact assessment with EDIP 2003 methodology

Fig. 7 represents the main impact categories obtained by applying the EDIP 2003 methodology. In this case, the *Global Warming Potential* has the highest value followed by the *Photochemical Ozone Formation* applied on two subcategories. The first is *Photochemical Ozone Formation human health*, which is modelled in line with the number of people extra exposed according to the WHO guide (WHO, 1989) for chronic effects time duration, expressed in pers·ppm·hours; the second is *Photochemical Ozone Formation vegetation,* which is identified as a specific ecosystem area overexposed for chronic effects time duration compared to the threshold given by WHO expressed in m^2·ppm·hours (ILCD Handbook, 2010b; 2011). Minor impacts are given by acidification potential, aquatic eutrophication, and terrestrial eutrophication. The presence of catalysts used for obtaining vinyl monomer has a significant contribution to the *Global Warming Potential*.

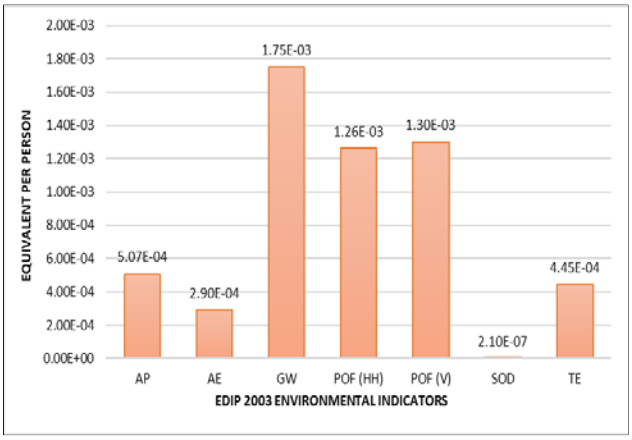

Fig. 7. EDIP 2003 methodology environmental impacts of PVC production

3.3. Environmental impact assessment with CML 2001 methodology

In this case, even if all impact categories shown in Fig. 8 have a positive value, they are quite small. Smaller contributions are given by: *Abiotic Depletion* (ADP), *Freshwater Aquatic Ecotoxicity* (FAE), *Marine Aquatic Ecotoxicity* (MAE), and *Terrestrial Ecotoxicity Potential* (TETP). The high values of FAE and MAE are given by the high content of nitrogen and phosphorus resulting from additives added in the polymerization process.

The outcoming scenario shows that the PVC life cycle analyzed (from the extraction of the raw materials until the end of the production) is environmentally harmful due to many polluting actors involved throughout the whole process. Figure 8 shows, for instance, a comparison of the impact assessment on human health between the ReCiPe and CML models. Chemicals (phthalates, ethylene, stabilizers, pigments) used in the production of PVC release emissions into the environment that have a negative impact on human health. Also, the process of obtaining PVC induces negative effects in the environment associated with the impact category of human health (Fig. 9). The generation of this type of impact is the consequence of chlorine emissions from the electrolysis stage of sodium chloride.

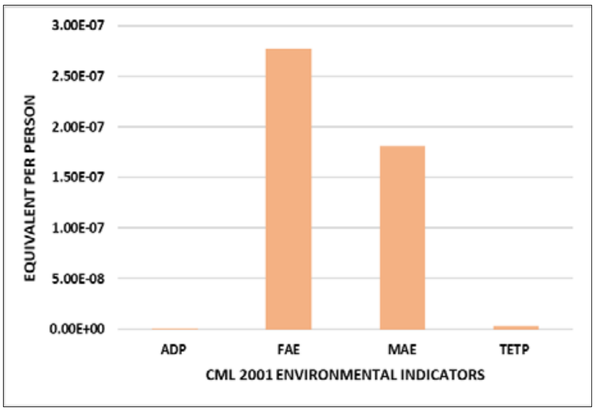

Fig. 8. CML 2001 methodology - environmental impacts of PVC production

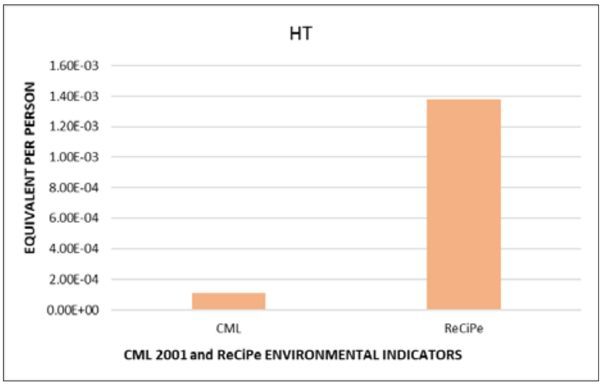

Fig. 9. Comparative evaluation of the impact on human health - ReCiPe vs CML

3.4. Suggestions for virgin PVC replacement

The results confirmed the big issue represented by the use of harmful feedstock in the plastic industry. Raw materials were a crucial topic ever since the very beginning of plastic; it was proved that more than 95% of the plastic present worldwide is fossil-based plastic (Plastics Europe, 2018).

In spite of this, innovation and research have started to undertake a very clear direction by boosting sustainability at its maximum rate and creating more environmentally sound solutions for today's global issues (Fortuna et al., 2012). Within the current circular economy perspective, also plastic has found a new way to reshape itself. One of the possible alternatives to fossil-based plastic is *bioplastics*. Bioplastics are that plastic that are either bio-based, biodegradable, or both (Europe Bioplastics, 2018).

Bio-based refers to the origin of the material, meaning that the raw material comes fully or partially from biomass, whereas biodegradable refers to the end of life of the plastic product. Biodegradable plastic is one able to chemically degrade itself thanks to microorganisms that turn the materials into water, carbon oxide, or compost (Europe Bioplastics, 2018).

Not all bioplastics are biodegradable and vice-versa. More specifically, according to Europe Bioplastics, bioplastics are divided in three categories: the first are those fully or partially bio-based but not biodegradable such as bio-based PE, PP, or PET, PA, PTT (mainly called drop-ins); the second type are both bio-based and biodegradable PHA, PLA and PBS; and finally, biodegradable fossil-based plastic such as PBAT (Europe Bioplastics, 2018).

Bioplastics do not even represent one percent of the total plastic on the market today albeit their production is getting wider (Jeremic et al., 2020). In particular, almost half of bioplastics present in the market are bio-based non-biodegradable (Fig. 10).

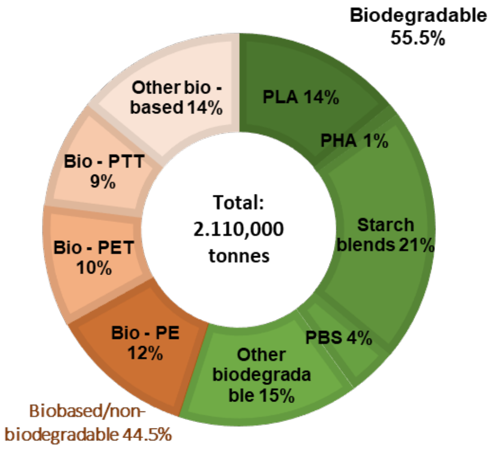

Fig. 10. Global production capacities of bio- plastics in 2019 (adapted upon Jeremic et al., 2020)

PCV can also derive from renewable feedstock and bio-PVC is expected soon to be produced boundlessly. When it comes to plastic manufacturing, plasticizers are definitely a critical issue. Particularly, in PVC production, 75% of the plasticizers used are phthalate plasticizers which are fossil-based substances (Feng et al., 2018). To overcome this, new studies and researches started to focus on developing bio-based plasticizers, which, generally, come from agricultural waste and by-products (Feng et al., 2018). The research is still open and keen to upscale bio-plasticizers to perform as well as petroleum-based plasticizers.

Obviously, bioplastics have several advantages. They contribute to resource-saving in input and to reduce GHG emissions and the overall carbon footprint of products in output (European Bioplastics, 2018). However, bioplastics are not the solution in absolute terms, and they need to be properly managed. They may become an issue in the end-of-life management; thus, it is of paramount importance to address clean and correct waste management in order to lower any potential environmental and human-related damage that they might cause. Bioplastics are able to biodegrade only in specific controlled conditions, and, consequently, they represent a serious problem if discharged erroneously (Ghinea et al., 2016; RameshKumar et al., 2020). The recycling option is considered to be the preferred solution for bioplastic. Recycling can be performed mechanically, chemically, or organically according to the most favorable condition and the composition of the specific plastic product (RameshKumar et al., 2020).

The life cycle assessment methodology, once again, represents a great tool, since it is able to analyze and assess the impacts related to bioplastic-based products throughout their entire life cycle. The paper thereupon invites to perform additional LCA-based analyses aimed at comparing the environmental performances between bio-PVC products and virgin PVC products.

5. Conclusions

This paper focuses on a specific kind of plastic which is Polyvinyl Chloride (PVC). The PVC production involves several steps and processes: raw material extraction, different sub-steps to produce EDC, and VCM and, lastly, the PVC manufacturing to obtain the final product.

In order to evaluate the environmental impacts related to the PVC industry, a Cradle-to-Gate analysis has been performed with the support of the GaBi software and the use of three characterization methods (ReCiPe 1.0, EDIP 2003, and CML 2001).

According to ReCipPe 1.08, fossil depletion is the most significant indicator, due to the fact that a huge amount of crude oil is involved in the extraction process. EDIP 2003 shows that climate change is the biggest contributor and it is related to a large number of emissions released into the environment during the production and the extraction phases. Lastly, as far as CML 2001 is concerned, in accordance with ReCiPe 1.08, human toxicity is an endangered impact category because of several toxic substances involved in the whole process.

The final part describes one of the most valid alternatives able to partially fix the environmental issue related to the PVC industry: the substitution of the raw material. Bioplastic solution is a strong option to take into consideration; past studies provided quantitative information about its efficiency and advantages. However, researching for new innovative alternatives and improving the already existing ones is an energy-demanding and time-consuming procedure. Nevertheless, there is considerable room for improvement. Therefore, this project encourages the public and the private sector to work deeper in order to change direction and reverse the current damaging trend.

This study helps to understand the major impacts that just a kilogram of PVC might have. Consequently, the study highlights the urgent need to shift direction and invest in more environmentally sound solutions in PVC production.

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References

Alsabri A., Al-Ghamdi S.G., (2020), Carbon footprint and embodied energy of PVC, PE, and PP piping: Perspective on environmental performance, *Energy Reports*, **6**, 364-370.

Boustead I., (2005), Eco-profiles of the European Plastics Industry POLYVINYLCHLORIDE (PVC) (EMULSION POLYMERISATION) Report, On line at: http://www.inference.org.uk/sustainable/LCA/elcd/external_docs/epvc_31116f09-fabd-11da-974d-0800200c9a66.pdf.

CR, (2014), Ceresana Research, Global demand for PVC to rise by about 3.2%/year to 2021. *Additives for Polym*ers, https://doi.org/10.1016/S0306-3747(14)70175-7.

Comanita E.D., Ghinea C., Roșca M., Simion I.M., Petraru M., Gavrilescu M., (2015), Environmental impacts of polyvinyl chloride (PVC) production process. *E-Health and Bioengineering Conference* (EHB), http://doi.org/10.1109/EHB.2015.7391486.

Comanita E.D., Ghinea C., Roșca M., Smaranda C., Favier L., Gostin I., Iordache S., Gavrilescu M., (2016a), Impacts on climate change generated by polyvinyl chloride (PVC) and polyhydroxyalkanoates (PHAs) production: A comparative approach, *Scientific Papers. Agronomy Series*, **58**, 253-260.

Comanita E.D., Ghinea C., Hlihor R.M., Gavrilescu M., (2016b), Occurrence of plastic waste in the environment: ecological and health risks, *Environmental Engineering and Management Journal*, **15**, 675 – 687.

CEC, (2000), Commission of the European Communities, Green Paper Environmental issues of PVC, On line at: https://ec.europa.eu/environment/waste/pvc/pdf/en.pdf

Elashmawi I.S., Alatawi N.S., Elsayed N.H., (2017), Preparation and characterization of polymer nanocomposites based on PVDF/PVC doped with graphene nanoparticles, *Results in Physics*, **7**, 636 – 640.

EMAF, (2016), Ellen MacArthur Foundation, the New Plastics Economy: Rethinking the Future of Plastics. Ellen MacArthur Foundation, On line at: https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics.

European Bioplastics, (2018), Fact Sheet, On line at: https://docs.european-bioplastics.org/publications/fs/EuBP_FS_What_are_bioplastics.pdf.

ECVM, (2000), European Council of Vinyl Manufactures The European Stabilisers Producers Associations (ESPA), The European Council for Plasticisers and Intermediates (ECPI), European Plastics Converters (EuPC), Voluntary Commitments Sustainable Development from the PVC industry, On line at:. https://vinylplus.eu/uploads/Modules/Documents/Executive_Summary/Sustainable%20Development,%20Voluntary%20commitments%20from%20the%20PVC%20industry/sd_uk.pdf.

Falcke H., Holbrook S., Clenahan I., Carretero A. L., Sanalan T., Brinkmann T., Roth J., Zerger B., Roudier S., Sancho L.D., (2017), Best Available Techniques (BAT) Reference Document for the Production of Large Volume Organic Chemicals – Industrial Emissions Directive, On line at: https://publications.jrc.ec.europa.eu/repository/handle/JRC109279.

Feng G., Hu L., Ma Y., Jia P.,Hu Y.,Zhang M.,Liu C.,Zhou Y., (2018), An efficient bio-based plasticizer for poly (vinyl chloride) from waste cooking oil and citric acid: Synthesis and evaluation in PVC films, *Journal of Cleaner Production*, **189**, 334 -343.

Fortuna M.E., Simion I.M., Ghinea C., Petraru M., Cozma P., Apostol L.C., Hlihor R.M., Fertu D.T., Gavrilescu, M., (2012), Analysis and management of specific processes from environmental engineering and protection based on sustainability indicators, *Environmental Engineering and Management Journal*, **11**, 333-350.

Ghinea C., Sprânceană A., Comăniță D.E., Constantinescu G., Gavrilescu M., (2015), Assessment of environmental impacts of municipal solid waste management in Iasi, Romania, *Food and Environment Safety*, **14**, 171-180.

Ghinea C., Dragoi E.N., Comăniţă E.D., Gavrilescu M., Campean T., Curteanu S., Gavrilescu M., 2016. Forecasting municipal solid waste generation using prognostic tools and regression analysis, *Journal of Environmental Management*, **182**, 80-93.

Guangbao W., Shangsuo Y., Jijun X., (2020), Thermal degradation kinetics of calcium stearate/PVC composite, *Results in Materials*, **8**, 100123.

Hauschild M.Z., Rosenbaum R.K., Olsen S.I., (2018), *Life Cycle Assessment Theory and Practice*, Springer, doi: https://doi.org/10.1007/978-3-319-56475-3.

ILCD handbook, (2010a), International reference Life Cycle Data System, Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment,. On line at: https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-LCIA-Background-analysis-online-12March2010.pdf.

ILCD handbook, (2010b), International reference Life Cycle Data System, Framework and requirements for Life Cycle Impact Assessment models and Indicators, On line at: https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-LCIA-Framework-Requirements-ONLINE-March-2010-ISBN-fin-v1.0-EN.pdf.

ILCD handbook (2011), International reference Life Cycle Data System, Recommendations for Life Cycle Impact Assessment in the European context – based on existing environmental impact assessment models and factors, On line at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC61049/jrc61049_ilcd%20handbook%20final.pdf.

ISO 14040, (2006), Environmental Management – Life Cycle Assessment – Principles and Framework. Geneva: ISO, On line at: https://www.iso.org/standard/37456.html.

ISO: 14044, (2006), Environmental management – life cycle assessment – requirements and guidelines. Geneva: ISO, On line at: https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en.

Jeremic S., Milovanovic J., Mojicevic M., Skaro Bogojevic S., Nikodinovic – Runic J., 2020. Understanding

bioplastic materials – Current state and trends, *Journal of the Serbian Chemical Society*, **85**, 1507–1538.
Khaleghi M., Didehban K., Shabanian M., (2017), Effect of new melamine-terephthaldehyde resin modified graphene oxide on thermal and mechanical properties of PVC, *Polymer Testing*, **63**, 382-391.
Liu D., Jiang P., Nie Z., Wang H., Dai Z., Deng J., Cao Z., (2020), Synthesis of an efficient bio-based plasticizer derived from waste cooking oil and its performance testing in PVC, *Polymer Testing*, **90**, 106625.
McKeen L.W., (2012), *Polyolefins, Polyvinyls, and Acrylics*, In*: Permeability Properties of Plastics and Elastomers*, 3rd Edition, Elsevier, Amsterdam.
Megange P., Ngae P., Feiz A., Le T., (2020), Dynamic site-dependent Life Cycle Assessment for assessing impact of human toxicity of a double glazed PVC window, *Procedia CIRP*, **90**, 316-321.
Mohammed A.A., (2019), *Mechanical strength of concrete with PVC aggregates*, In: *Use of Recycled Plastics in Eco-efficient Concrete*, Pacheco-Torgal F., Khatib J., Colangelo F., Tuladhar R., Elsevier, United Kingdom, 115-135.
Pascault J.-P., Höfer R., Fuertes P., (2012), *Polymers for a Sustainable Environment and Green Energy*, Elsevier, https://doi.org/10.1016/B978-0-444-53349-4.00301-0.
Peng B., Chen Z., Chen J., Yu H., Zhou X., Criddle C., Wu W., Zhang Y., (2020), Biodegradation of Polyvinyl Chloride (PVC) in *Tenebrio molitor* (Coleoptera: Tenebrionidae) larvae, *Environment International*, **145**, 106106, https://doi.org/10.1016/j.envint.2020.106106
Pereira V., Fonseca A., Costa C., Ramalho A., Coelho J., Serra A., (2020), End-capped biobased saturated polyesters as effective plasticizers for PVC, *Polymer Testing*, **85**, 106406, https://doi.org/10.1016/j.polymertesting.2020.106406
Pita V.J.R.R., Sampaio E.E.M., Monteiro E.E.C., (2002), Mechanical properties evaluation of PVC/plasticizers and PVC/thermoplastic polyurethane blends from extrusion processing, *Polymer Testing*, **21**, 545-550.
PlasticsEurope, (2018), Bio – Based Plastics, On line at: https://www.plasticseurope.org/en/about-plastics/what-are-plastics/large-family/bio-based-plastics.
PlasticsEurope, (2019), Plastics – the Facts, An analysis of the European plastics production, demand and waste data, On line at: https://www.plasticseurope.org/application/files/9715/7129/9584/FINAL_web_version_Plastics_the_facts2019_14102019.pdf.
Prieto D., Swinnen N., Blanco L., Hermosilla D., Cauwenberg P., Blanco Á., Negro C., (2016), Drivers and economic aspects for the implementation of advanced wastewater treatment and water reuse in a PVC plant, *Water Resources and Industry*, **14**, 26-30.
RameshKumar S., Shaiju P., O'Connor K.E., Ramesh Babu P, (2020), Bio-based and biodegradable polymers – State – of – the - art, challenges and emerging trends, *Green and Sustainable Chemistry*, **21**, 75–81.
Rangaswamy J., Kumar T., Bhalla K., (2018), A comprehensive Life-Cycle Assessment of locally oriented small-scale toy industries: A study of traditional *Channapatna* toys as against low-cost PVC (Poly-Vinyl Chloride) Toys made in China, *Procedia CIRP*, **69**, 487-492.
Samani P., Meer Y., (2019), Life cycle assessment (LCA) studies on flame retardants: A systematic review, *Journal of Cleaner Production*, **274**, 1232259.
Stichnothe H., Azapagic A., (2012), Life cycle assessment of recycling PVC window frames, *Resources, Conservation and Recycling*, **71**, 40-47.
Venkatachalam V., Spierling S., Horn R., Endres H., (2018), LCA and eco-design: consequential and attributional approaches for bio- based plastics, *Procedia CIRP*, **69**, 579-584.
VEC, (2008), Vinyl Environmental Council Japan, PVC Fact Book, On line at: https://www.vec.gr.jp/english/fact/pvc_fact_book_e-all.pdf.
Vinyl Plus, (2017), PVC recycling technologies, On line at: https://vinylplus.eu/uploads/downloads/VinylPlus_Recycling_Technologies_30012017.pdf.
Vinyl Plus, (2020), Vinyl Plus, Progress Report, reporting on 2019 activities, 2020, On line at: https://vinylplus.eu/uploads/images/progreport2020/VinylPlus%20Progress%20Report%202020_EN_sp.pdf.
WHO, (1989), World health organization Technical Report Series – Health of the elderly, On line at: https://apps.who.int/iris/bitstream/handle/10665/39521/WHO_TRS_779.pdf;jsessionid=A14D575F91769E44661ECC39E95B5C07?sequence=1.