Management and environmental impact of post-consumer Polyvinyl Chloride (PVC) waste.

MINIREVIEW

Module E02 – Environmental risk of plastic materials

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Content

0. Abstract

The following minireview is based on describing the environmental impact of post-consumer PVC waste in two scenarios: when (1) the waste is subjected to good management waste practices, and when (2) poor management makes waste a pollutant in the aquatic ecosphere.

1. Introduction

Synthetic plastics are essential materials in daily life and industry, with global production exceeding 300 million tons per year according to a study carried out in 2018. In Europe, polyvinyl chloride (PVC) is the third most demanded polymer while, in a global perspective ranks in the second position with almost 25 million tonnes produced per year (Peng *et al.*, 2020; Sadat-Shojai and Bakhshandeh, 2011).

Polyvinyl chloride is a thermoplastic polymer characterized by not being soluble neither in alcohol nor in water. This polymer is composed of repetitive ethenyl wherein hydrogen is replaced by chlorine on alternate carbons per monomer, being estimated the percentage of halogenated elements in more than 56% of chlorine elements in its polymeric structure (Peng *et al.*, 2020; Akovali, 2012). Being regarded as one of the most demanded polymers is justified by its low cost and high efficiency due to its good chemical, thermal, mechanical, and electrical properties. This fact provokes it to be used in a wide range of fields such as construction, edification, packaging, electronics, and automotive, allocating more than 60 % of PVC production in the first two fields aforementioned (Miliute-Plepiene, Fråne and Almasi, 2021; Sadat-Shojai and Bakhshandeh, 2011).

The real-life of PVC is averaged in ten years, but this thermoplastic is classified depending on its application lifespan. It is considered a short-life product when is used in medical devices, textile, food, or beverage packaging, while long-life products predominate in the use of floor coverings or window frames (Sadat-Shojai and Bakhshandeh, 2011). In both cases, PVC will become post-consumer PVC waste that has two fates. On one hand, if good management waste practices are applied, waste will be fated to be recycled, landfilled, biodegraded, or incinerated (Peng *et al.*, 2020). On other hand, poor management waste practices will destinate the post-consumer PVC waste as a pollutant in different ecospheres such as water, air, or land.

To the aforementioned content, post-consumer PVC waste management has generated concern by boosting environmental crisis due to its dioxins release or organochlorine emissions. In addition, PVC as a pollutant in the marine ecosphere can lead to the formation of microplastics that enter into the food chain. This minireview collects information related to the environmental impact of PVC waste, based on articles published in the last thirteen years.

2. PVC classification.

The resin of PVC is a white, odorless, and amorphous powder, with thermal stability until 80ºC. Decomposition and subsequent hydrochloric acid formation take place when this temperature is overcome (Akovali, 2012). Before delving into environmental impact, it is necessary to differentiate two types of resins available in the market: rigid and flexible.

Rigid PVC resin, also known as non-modified PVC, is characterized by its high hardness and strength. Both particularities cause rigid PVC sheets to be used in pipe construction, doors and windows profiles, automotive parts, or packing, excluding food packaging applications (Akovali, 2012 ; Peng *et al.*, 2020). Related to flexible PVC resin, they are determined by being heat and UV stable, soft, and flexible, due to the high quantity of additives in its structure. These soft polymers are applied in canvas making, toys, and hoses, in replacement of rubber, or clothing such as artificial leather (Peng *et al.*, 2020).

Additives

Modifying PVC properties requires the use of additives to color plastics (colorants), stabilizing plastics against the light and temperature influence (stabilizers), and as protectors of elasticity (plasticizers). The presence of these additives causes one environmental concern because they are not chemically bonded with the polymer, which can lead to their release from PVC products to polymer surface, water, or air.

Stabilizers are structurally formed by the presence of heavy metals such as lead, zinc, or organonickel compounds, whereas plasticizers are esterified additives, like mellitates and phthalates, being the last the most used (Akovali, 2012). The release of these additives leads to health effects like the specific case of phthalates esters (PAEs), which are restricted by EU REACH regulation, or stabilizers (ODTs) which cause endocrine-disrupting such as reducing reproductivity and/or affecting neurobehavior; Peng *et al.*, 2020; Zhang, Zhang and Zhang, 2021).

Due to the impacts caused by additives in PVC, European Union (EU) created new waste management that cites appropriate eco-friendly measures to reduce these impacts. These measures include the progressive elimination of lead and cadmium stabilizers or the evaluation of new plasticizers (Janajreh, Alshrah, and Zamzam, 2015). Notwithstanding the measures, the use of hazardous additives before the 2000s today complicates the management of this older PVC due to the probability of lead or phthalates both of which are currently limited in use (Miliute-Plepiene, Fråne and Almasi, 2021; Miliute-Plepiene, Fråne and Almasi, 2021).

3. First scenario: good waste management practices and environmental impact.

Different ways to manage the PVC waste include incineration, landfilling, recycling, and biodegradation, but there will be some limitations (Figure 1) on their applications that will cause an impact on the environment.

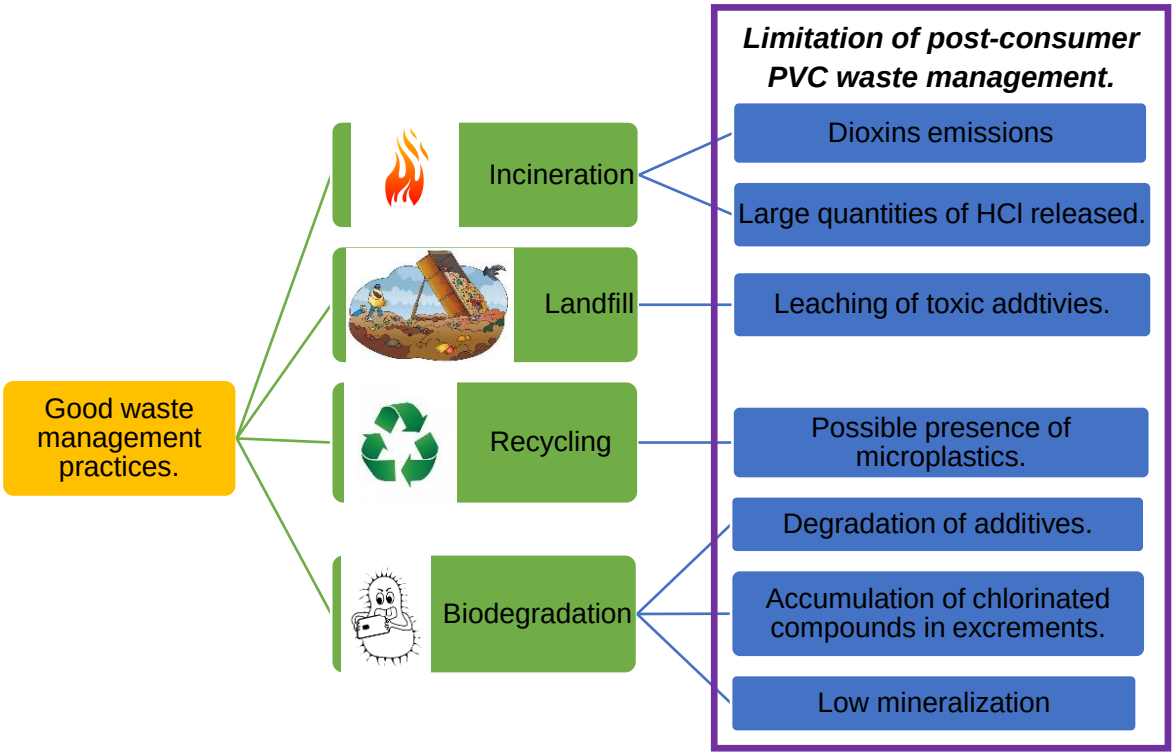

Figure 1. Limitations of post-consumer PVC waste management.

Incineration

PVC incineration process is based on the destruction of the organic fraction and conversion of chlorine into gaseous hydrochloric acid which subsequently will be released with heat produced altogether. Historically and until now, PVC incineration has been considered an environmental concern due to the presence of heavy metals in fly ash, the formation of toxic and persistent compounds such as furans and dioxins, and the large quantities of hydrogen chloride released in the environment (Sadat-Shojai and Bakhshandeh, 2011; Miliute-Plepiene, Fråne, and Almasi, 2021; Buekens and Cen, 2011).

According to the UE directive, that material with a chlorine content greater than 1 % in their organic structure, they must be destroyed at a minimum temperature of 1100ºC. This requirement limits the treatment of PVC to valorise it energetically because the materials recovered as energy are subjected to low temperatures (Miliute-Plepiene, Fråne and Almasi, 2021). Thus, incineration is a non-feasible environmental technique because of the formation of pollutants and toxic compounds released into the environment.

Landfilling

Post-consumer PVC waste can be eliminated with landfills, but it is not considered a real long-term solution. This option is not acceptable to many countries due to the high cost of material involved in the process, the scarcity of available area in landfills, and hazards related to its chlorine content and the toxic additives released from the polymer (Zhang, Zhang and Zhang, 2021; Sadat-Shojai and Bakhshandeh, 2011). About the last point, landfills are not inert areas, and thus, toxic additives can leach out and contaminate the soil as well as waste sources (Akovali, 2012).

Recycling

Waste management from recycling prevents the environmental pollution caused by the two previous techniques. There are two types of recycling, mechanical and chemical (Yadav *et al.*, 2018 ; Sadat-Shojai and Bakhshandeh, 2011).

Mechanical recycling is useful when post-consumer PVC waste is enough homogeneous. Even so, it is considered an ecological alternative that does not cause changes in its chemical composition, but in its morphological structure due to the high environmental sensitivity of the material used in the process (Sadat-Shojai and Bakhshandeh, 2011;Zhang, Zhang and Zhang, 2021). In this recycling process, large amounts of non-treated wastewater will take place and thus, may contain an important quantity of microplastics that subsequently cause toxicity in marine fauna (Suzuki *et al.*, 2022).

Chemical recycling is based on transforming PVC waste into short chains to reuse in other chemical approaches, such as the petrochemical field (Janajreh, Alshrah and Zamzam, 2015; Sadat-Shojai and Bakhshandeh, 2011). Compared to mechanical recycling, this technique is less sensitive to contaminated plastics. It is considered a green alternative due to the low emissions but is not recommended because of its high price and energy-consuming during the process (Sadat-Shojai and Bakhshandeh, 2011).

Biodegradation

Apart from the second pollutants formed in landfilling and incineration, microplastic formation is another environmental concern. Researchers have focused on the toxic effects that can happen when these fragments leach out in landfills and enter the marine fauna. To remedy this problem, biodegradation has been studied to evaluate the fate of plastics in different environments (Giacomucci *et al.*, 2019; Peng *et al.*, 2020).

PVC is difficult to biodegrade because is a persistent, hydrophobic, and abrasion-resistant plastic. Notwithstanding these limitations, previous studies reported that PVC biodegradation is subjected to microorganisms cultures that are degraded into low molecular weight organic compounds that, consequently, will be mineralized to CO_2 (Yadav *et al.*, 2018; Peng *et al.*, 2020).

A study made by Giacomucci et al. 2019 evaluated the biodegradation of films PVC waste with 30% of plasticizers, in presence of *Pseudomonas citronellolis* bacteria. This study concludes that biodegradation activity is due to the presence of the additive and not to the PVC polymeric chains (Giacomucci *et al.*, 2019). In 2020, Peng et al. used PVC without plasticizers and demonstrated the depolymerization in presence of *Tenebrius molitos* larvae. This fact occasionally limited mineralization and the accumulation of chlorinated organic compounds in the larvae excrements. Low mineralization is due to the potential toxicity in the aerobic degradation of organic chloride compounds (Peng *et al.*, 2020).

4. Second scenario: poor waste management practices.

Poor waste management is due to inadequate disposal of plastic waste, coastal landfills that cause the leaching of PVC fragments and end up in the marine environment, or due to garbage transported by streams or rivers (Giacomucci *et al.*, 2019; Ganesh Kumar *et al.*, 2020).

Poor management can affect different ecospheres, but a great impact on marine fauna has been estimated. Fragmentation of plastics into micro-and nano- sizes allows them to overcome biological barriers, and accumulate in tissues or even in organs. Therefore, they can cause physical damage, sublethal effects, or even, death (Ganesh Kumar *et al.*, 2020).

Some studies have demonstrated toxic effects on the marine environment, like the case reported by Wang et al. 2020 where PVC microplastics had negative effects on *Chlamydomonas Reinhardtii* freshwater algae, leading to a reduction of chlorophyll content in its cells and thus, limiting the growth of these algae. Inhibition was determined by the increment in enzymatic activities of superoxide dismutase (SOD) and malondialdehyde (MDA), since reflecting the capability of eliminating oxygen free radicals and the ability to be a marker in lipid oxidative damage, respectively (Wang et al., 2020). Recently, all studies were limited to evaluating the impact on microorganisms, but a study published this year was the pioneer in evaluating ex vivo toxicity in human blood lymphocytes. In this study, it was concluded that microplastic PVC causes organelle damage in human lymphoid cells, such as the collapse of the mitochondrial membrane, lysosomal damage, lipid peroxidation, and oxidative stress due to the formation of intracellular reactive oxygen species (ROS). The aforementioned process leads to cytotoxicity in the microorganisms (Salimi *et al.*, 2022). According to this information collected, possible expected scenarios are represented in Figure 2.

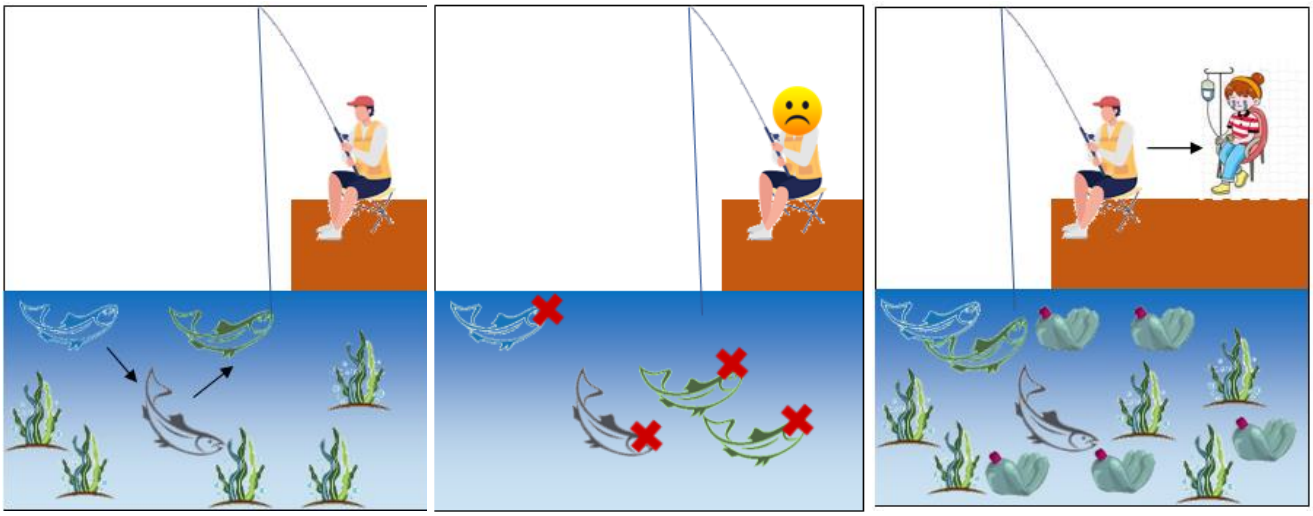

Figure 2. Scenarios produced in the marine ecosphere. (A) The ideal situation, without contamination, (B) PVC inhibits the growth of Chlamydomonas Reinhardtii algae which is the fish food, causing the death of these living organisms and (C) Fish eat microplastics PVC, interfering with the food chain and causing toxicity in humans.

5. Conclusions

The different ways of managing post-consumer PVC waste can generate second pollutants, such as the persistent organic pollutants (POPs) emissions or the microplastic formation. Many techniques explained in this review produce the second pollutants. Even so, the most ecological alternatives are recycling and biodegradation although there are limitations that must be overcome, for instance, by implementing chemically inactive oxides that can be chlorinated by the chlorine of PVC and serving as catalysts in the degradation of this material.

On the other hand, PVC microplastics are contaminants that must be remediated due to the toxicity generated in living organisms. As it has been evaluated, the formation of microplastics and their management of PVC waste is linked, even though good waste management practices are carried out.

Although attempts are being made to remediate and give a second life to PVC plastics, eco-friendly remediation without the formation of the second pollutant is a difficult task due to the presence of chlorine that limits this management. For this reason, the waste management of PVC should be further investigated.

6. References

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