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Systematic review: Analysis of the use of D-limonene to Reduce the Environmental Impact of Discarded Expanded Polystyrene (EPS).

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Abstract. The article presents a systematic review on the use of D-limonene with the aim of analyzing its efficiency to reduce the environmental impact of expanded polystyrene (EPS). Initially, an analysis of the life cycle of the EPS was carried out in a general way to identify the stage where the greatest impact on the environment is evident. Subsequently, primary sources were examined that raise the issue of reducing EPS using this green solvent, in view of the fact that it generates sustainability through recycling, optimization and application of various methods that could allow the circular economy of this waste in order to be applied in the industrial field and contribute to the socio-environmental aspect. Finally, the importance of this solvent was demonstrated according to the analysis and evaluation of each EPS recycling examining country.

1. Introduction

Expanded polystyrene (EPS), is a thermoplastic obtained from the styrene monomer polymerized with water and an expanding agent, composed of 98% air and 2% petroleum. It is lightweight, has low water absorption, density and large buffering capacity [1]. Within of its properties it has many applications both in the construction sector and in the production of food packaging or household appliances, being its first and last function [2]. It is considered a single life plastic, producing that, at the time of being discarded, it can end up in landfills or being part of "The North Pacific garbage patch", which is formed by the accumulation of plastics [3]. Worldwide until 2015, 407 million tons of plastic were manufactured, 6% of which was EPS [4]. According to Chemical Economics Handbook Polistyrene, the largest EPS market is the packaging market, which accounts for 37% of total demand globally [5].

The lack of recycling of EPS worldwide has caused them to end up on the coasts of the world such as Antarctica, 41% of what is collected belongs to all types of plastics, with 6% of EPS. Also, in the collection of solid waste carried out in Peru in 2014, it was reported that 9.12% are EPS residues found on the coast, which affects the marine ecosystem given that leaching tests showed the toxicity it presents to humans and marine life due to the substances that emanate when exposed to high temperatures [6]. In addition, it was recorded that until 2016 7,005,576 tons of solid waste were produced, of which only 1.9% is recycled [7]. On the other hand, in Peru due to the increase in the cost of collecting plastics the industry is considered unprofitable [8], which means that this EPS waste is still not recycled. Despite the fact that in 2018 the Peruvian State presented the “Law 30884" that prohibits the use of plastic, EPS and straws, it has been largely ignored, since efforts continue to be scarce [9].

Likewise, the sanitary provisions issued by the different governments to prevent and control COVID 19, including confinement, brought with it some benefits at the environmental level. However, the problem

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of solid waste became even more acute because in 2020 and 2021 delivery increased by 205%. The increase of this material has been so high that recycling systems have collapsed in some countries, mainly in Latin America. It is estimated that more than 70% of this plastic will end up being disposed of in oceans and landfills, and up to 12% will be incinerated, causing pollution and disease in the most vulnerable areas of the planet [10]. Taking into account the problems that are present, a solution is proposed for the recycling of discarded EPS, avoiding that it affects the marine ecosystem, since it occupies large spaces and its degradation takes 500 years [3]. Therefore, it is suggested to make use of D-Limonene because it is an environmentally friendly solvent, in addition to being effective and inexpensive for the treatment of EPS. The use of this natural oil as an alternative, is one of the most favorable and environmentally friendly for recycling.

2. Methodology

The present research was carried out through bibliographic compilation, the life cycle analysis of the EPS followed by the ISO 14040 standard [11] was systematized. Information on the recycling and application technique used by the authors of 12 articles and 5 theses was collected, indicating the countries in which this organic solvent was investigated. As can be seen in table 1.

2.1. EPS Lifecycle Analysis

Life cycle analysis allows us to identify opportunities to optimize the environmental performance of a product at different stages of its life cycle [11], evaluating the impacts of each of the processes involved from the acquisition of the raw material to its final disposal. In addition, it studies the effect it may have on the field of well-being, health of living beings and their ecosystem. According to ISO 14040, the life cycle of a product, in terms of expanded polystyrene, is classified into four main stages: material acquisition, manufacture, use and final disposal. Each of these stages impacts the environment significantly.

2.1.1. Acquisition of material and manufacture:

This stage involves the environmental costs associated with the raw material, since the level of environmental impact of the product will depend on the material used. As Chargoy mentions, within this first stage, a large number of environmental impacts are generated, caused by the process of polystyrene production by the use of gas [12], in the process of collecting EPS by fossil resources are derived, causing 96% of negative effects that are related to global warming [13].
The manufacturing process for the creation of EPS generates an impact on the environment since it requires a considerable amount of energy and produces harmful atmospheric emissions, which leads to the increase in acidification [14], since the energy that is required for the manufacture of this product is 1kg and the largest emission that is generated is Smog due to consumption de maquinarias [13].

2.1.2. Distribution and transport

At this stage, the production plants generate damage, due to fossil fuels. They generate an impact of 78% to the increase of global warming when the material is transported for distribution and 75% in transport for its final disposal, the gases that are emitted are CO and due to the combustion of vehicular engines $NO_xSO_xCO_2$ [13]. Similarly, the emission of these gases contributes to acidification and causes the formation of volatile compounds (VOCs).

2.1.3. Use of the Product

EPS is a product widely used in various industries, so there is an obvious concern about its effect. However, the effects on the environment during this stage are minimal, so an exhaustive bibliographic research has been done to approximate the possible environmental implications. The characteristics of the EPS make the industry use this material as packaging, with the aim of providing protection to the products that are transported from one place to another. If we analyze the transport of packages packed with EPS, the most important implications would be the following: resource consumption (crude oil, natural gas, coal, etc.) [14]

2.1.4. Final disposition

The level of environmental impact at this stage will depend on the type of waste disposal, whether it ends up in a landfill, in a landfill or if the EPS goes through a recycling process. The waste that is disposed of in a landfill generates an increase in global warming due to the emissions from which itCO_2 emanates [13]. The waste that is disposed of in open dumps has direct effects on our resources, and this waste takes up to 500 years to degrade [15]. In Singapore, the technology for their end-of-life is to incinerate them, causing further damage due to their high waste content and the combustion process that pollutes the air. It is estimated that 73% of its waste comes to be incinerated and 27% is directed to landfills, noting that there are no schemes to recycle packaging and there is no waste collector in order to recover the EPS [16].

This stage also has a significant impact on the aquatic ecosystem. This is because EPS, being composed of pentane () and styrene () makes an excessive contribution of macronutrients to the soil and air, which leads to eutrophication. The impact is high, as 94% of E$C_5H_{12}C_5H_8$PS waste is disposed in landfill. A study carried out in Singapore showed that the disposal of EPS in landfills contributes to the emission of greenhouse gases because it is a material that does not degrade easily so it remains inactive in the environment [14].

2.2. Organic solvent: D-Limonene

D-Limonene $\boldsymbol{C_{10}H_{16}}$ is a monocyclic terpene that has agreement with isoprene, which is found in natural sources such as citrus peel and has a great capacity to treat EPS [17] [18]. It is also worth highlighting its relevance in the commercial field for its antimicrobial properties, aroma, and its application as an oxidizing agent. It definitely plays an important role for socio-environmental health, since it has developed interest in the medical field for its various functions that benefit the human being [19]. Among its characteristics it presents a scarce yellow color that is soluble in water at 13.8 with a temperature of 24 ° C, the substance has a citrus smell and has a density of 0.842 to 0.846.$mg\ L^{-1}$

2.3. Information collected from the information:

Table 1: Source of Information collected.

Author and Year	Document type	Country	OBJECTIVES
(Lozada, 2017)	Thesis	Peru	To determine the appropriate proportion of limonene for the recovery of EPS.
(Arthur et al., 2019)	Thesis	Colombia	Analyze EPS recycling process with limonene for flower arrangements.
(Ciriminna et al., 2014)	Article	Colombia	Determine the most efficient green solvent by analyzing its properties.
(Pardo; Leon, 2021)	Article	Colombia	Analyze the facts of the EPS parameters using limonene and eucalyptus oil
(Avellaneda, 2017)	Thesis	Colombia	Dilute EPS with limonene for coating

			(protection and decoration)
(Arcila; Miranda, 2015)	Thesis	Colombia	Evaluate the production of paint with EPS residues by applying limonene
(Gómez et al, 2021)	Thesis	El Salvador	Apply limonene for EPS recycling effectiveness
(Parada et al., 2019)	Article	Ecuador	Recycle EPS with limonene for resin with anticorrosive coating
(Olsson et al; 2015)	Article	Brazil	Extract limonene and EPS to obtain paint
(Cebrian et al, 2021)	Article	Brazil	Improve substrate for OLEDs by coating it with EPS dissolved in D-limonene.
(Carrillo, 2013)	Article	Mexico	Evaluate proposals that resolve the accumulation of the EPS.
(Hardjono et al, 2021)	Article	Indonesia	Destroy EPS foam waste with D-Limonene use
(Sutakhote et al, 2020)	Article	Thailand	Develop a braille block with EPS and coconut fiber
(Hearon et al, 2014)	Article	United States	Develop high-performance recycling for EPS.
(Shin et al, 2005)	Article	United States	Develop recycled EPS nanofiber
(Chylińska; Trojanowski; Podgórski, Niemcewicz, 2018)	Article	Poland	Analyze polymer recycling methods.
(Pääkkönen, 2019)	Article	Finland	Investigate whether Japan's EPS waste management method is appropriate in Finland

Own elaboration

3. Results

3.1. Countries examining the Recycling de EPS applying D-Limonene

As reviewed, countries are investigating this organic solvent for the recycling of EPS more frequently in recent years, with the aim of contributing in a social, environmental, and economic way to. Waste with inadequate final disposal has environmental implications that are of great significance, generating a large-scale problem taking into account the difficulty for its degradation. D-Limonene is widely used as a biodegradable solvent, having a nature-friendly behavior [20]. As can be seen in figure 1.

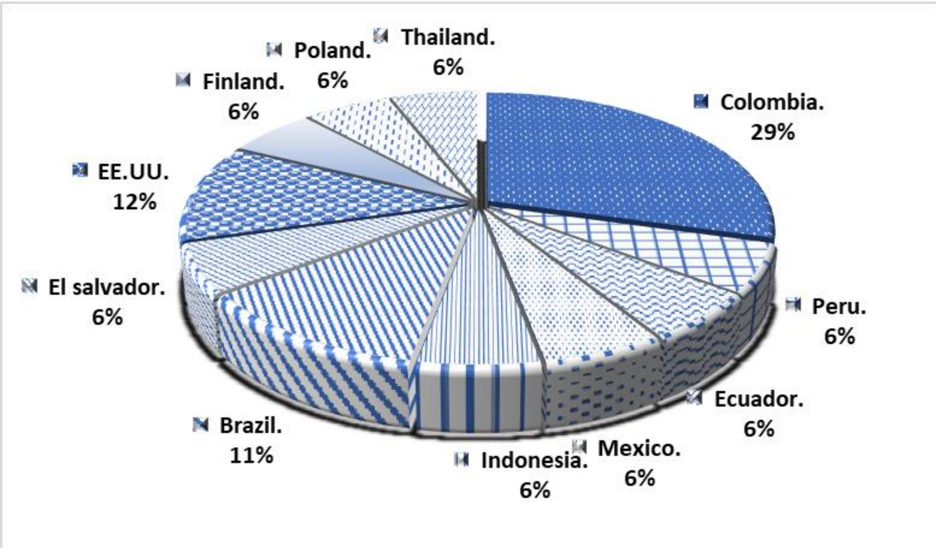

Figure 1: Percentage of participation of examining countries on EPS recycling.

The figure 1 indicates the country with the most research on the recycling of EPS with limonene is Colombia with 25%, this is carried out by its environmental policies. Also, it represents a great advantage over other countries and the main influence for research in Latin America, while U.S. accounts for 12% ahead of European countries.

3.2. D-Limonene and its application:

The information gathered on the use and application of D-limonene to reduce EPS indicates that this compound is environmentally friendly, in addition to its accessibility and low implementation costs.

Limonene is the most used solvent and with the highest approval within tertiary treatment, because it changes the chemical composition generating a second matter with a lower percentage of contamination [2][21]. Gómez sought to know the methods of extracting limonene to be able to recycle EPS, which showed that, if there is a reduction in the volume of EPS, demonstrating that it is possible to extract limonene and use it for the recycling of EPS [20]. Pardo and León highlight a comparison about the solubility of D-Limonene compared to that of eucalyptus oil with a ratio of 93 g of EPS per 100g of eucalyptus oil and 150g of EPS per 100g of limonene, subjected to a temperature of 21°C, demonstrating better solubility. Likewise, it is interpreted that this solvent has a lower energy value with 22.9 kJ/mol, unlike eucalyptus with 37.25 kJ/mol, indicating less need for energy from limonene to be able to perform the solution [21] . De according to Hearon's analysis for the recycling of EPS that are used as packaged food and beverages are soluble in aromatic solvents taking samples up to 30% eps with a temperature of 25 ° C with a range of 370MPa, suitable results for large-scale application as it is a promising and cost-effective treatment compared to other methods [22].

Hardjono emphasizes disintegrating polystyrene based on the essential oil of D-Limonene, ethanol and water, in proportions of (1,0,0; 1,0,3; 1,1,2; 1,2,1), analyzing the time it takes to disintegrate EPS into its various forms that he established as: food packaging, electronic packaging, foam boards and cup noodles, demonstrating that the most suitable ratio for disintegration is (1,1,2), with a higher percentage of destruction of 9.37% for electronic packaging [23]. Therefore, it is proposed to use this green solvent to recycle the EPS and thus give rise to the circulating economy in Peru as it is in the case of European countries. Olsson argues that for EPS waste, it is possible to use a new destination based on this solvent for the production of paint in the field of civil construction and furniture sector creating a sustainable development with profitable viability [24]. The following lines detail the research that contributes to the recycling of EPS dissolved in D-limonene as it optimizes or transforms the characteristics of existing products.

Carrillo evaluated the tensile properties of a Kraft paper when coated with an EPS-based resin dissolved in D-limonene. The result obtained shows a significant increase in paper strength [25]. Similarly, a similar study is presented in Peru on a smaller scale analyzing the optimum ratio for the degradation of the paper, with this solvent using the necessary amount 1:1 to achieve a dissolution without increasing residues [26].

Parada unveils the development of corrosive EPS coating as an option to reduce large amounts of polymers that are discarded on a daily basis. To do this, he used EPS as resin, solvent (D-Limonene) and pigments (and TiO_2 ZnO). He was able to determine the effectiveness of the anticorrosive material in saline environments by evaluating the physical, chemical, and rheological properties, which showed that the EPS formulation has ideal corrosion resistance characteristics. In addition, he compared the anticorrosive material formulated by EPS with a commercial one, and determined that the former possesses superior performance [27]. Similar research in other countries supports the above proposal. These results are reflected in research carried out by Carrillo and Avellaneda [25] [28].

Bacterial cellulose (BC) has been used over the years as a substrate for flexible organic light-emitting diodes (OLEDs). Such membranes are non-toxic and possess good mechanical properties. However, being semi-transparent they limit their performance, so Cebrian [28] proposes to improve the optical properties of the BC membrane by coating it with recycled petrochemical plastics (polystyrene)dissolved with d-limonene. The feasibility of using EPS-modified BC as a substrate for OLED was demonstrated, because it has better characteristics. This manufacturing approach is a sustainable technique for developing high-performance transparent substrates.

Sutakhote developed a braille block from recycled polystyrene foam by dissolving the foam in D-limonene and reinforcing with coconut pitch, physical properties (tension, elongation at breakage and compression) were analyzed in various proportions. The ideal ratio to build the braille block was 1: 1/2, that is, you need 3.5 g of EPS and 1.75 g of coconut. This research represents a sustainable alternative to reduce the amount of EPS foam [29]

In another work, Shin and Chase transformed EPS residues into polystyrene nanofibers to modify the fiberglass filter media. D-limonene was used as a solvent for the PS nanofiber electro-spinning technique. According to the authors, it is an economically viable method for producing nanofibers (the diameter was approximately 700 nm), in addition, the results showed that the addition of EPS nanofibers improved the efficiency of the filter media by 68 to 88% [30] The production of paint based on the solvent limonene with expanded polystyrene was examined, comparing the conventional paint with the modified one, obtaining a drying time of 143.5min deferred from the commercial one with a time of 240min, a similar adhesion time with 4.5 and 4.6 respectively, the viscosity of the suggested paint, had a great difference having a 11399.3 centistokes compared to commercial paint with a 3161.9 centistokes, the covering power was superior for the suggested with a measure of 7.3 compared to 4.6 of the commercial, it is manifested that the viscosity can in this state, it can be re-foamed, processed by extrusion or a new product can be obtained as a result of subsequent technological steps [31]. In short, according to Chilinska, the most economical way to recycle EPS is by dissolving it, since this process significantly reduces the volume. In that state, it can be re-foamed, processed by extrusion or a new product can be obtained as a result of subsequent technological steps [32]

4. Conclusions and Discussions

This research details the use of limonene as a green solvent for recycling and reduction applications of expanded polystyrene. Each research from different countries was analyzed in detail, concluding that this solvent is widely examined in Latin American countries such as Colombia, Brazil, El Salvador and

Mexico because this solvent does not generate a significant impact on the environment due to its biodegradation. Subsequently, a study of limonene in European and American countries was analyzed from a broader approach determining that this solvent significantly reduces the accumulation of EPS, because it has better solubility compared to other oils detailing the appropriate proportion and thus in the face of these global challenges present a system of reuse of resources, generating an added value to the secondary matter that is obtained, allowing the circular economy. Also, it should be emphasized that such solvent is the most used within the tertiary treatment for the reduction of these of polystyrene waste due to its feasibility and implementation of use as in the management of Japan. Therefore this information denotes interest and importance of the value of use of this biodegradable substance for its application in the field of recycling management.

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