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Rescuing the Environment: Turning (Micro)plastics into Energy Through Gasification

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Abstract

Plastics are a common residue of our activities and, when incorrectly disposed, high quantities of this type of products end up in the environment, namely through landfilling and dumping into the aquatic compartments. Therefore, water streams and basins are contaminated threatening wildlife, which ultimately can entail human toxicity by means of the food-chain effect. One of the major concerns relies on microplastics which, due to its size and nature, constitute a more difficult to handle residue.

This paper presents an endeavour to control, reduce or even mitigate the presence of plastic debris in the environment, with the benefit of converting them into energy or other valuable commodities for the actual society. Gasification can be seen as one of the most effective techniques for this purpose, featuring a more environmental friendly scheme for treating this kind of residues, avoiding their overspread throughout Nature, as well as complying with environmental policies.

Author Keywords. Sustainability, Microplastics, Gasification

Type: Research Article

1. Introduction

The economic and social development seen in the last decades are thoroughly linked to the common use of products and technologies that enable easier ways of living, learning and working. Plastic and general synthetic goods are between the major humankind allies, being present in packaging, hygiene products, clothes, household appliances, and also as components of technological equipment like laptops, cell phones or any other current gadgets. Depending on the final purpose different plastics are used, which increments their contribution to the diversity and quantity of waste generated worldwide, hence complicating its management and safe disposal.

The plastics industry has shown a progressive development for more than 50 years, and is part of the top 5 most innovative sectors in the EU, reaching a production of 300million tonnes in 2015 (PlasticsEurope 2016; Eerkes-Medrano, Thompson, and Aldridge 2015). That year, the total plastic demand in Europe was 49 million tonnes, six countries concentrating 70% of the total demand, as shown in Figure 1. The remaining 30% represented plastic necessities for 24 other countries. In developed countries, a high percentage of plastic waste is recycled or valorised energetically, EU accomplishing an average 69% share (PlasticsEurope 2016), nevertheless in developing countries a significant percentage is still landfilled or sent to other environmental compartments, affecting all the ecosystems (Kadir et al. 2013).

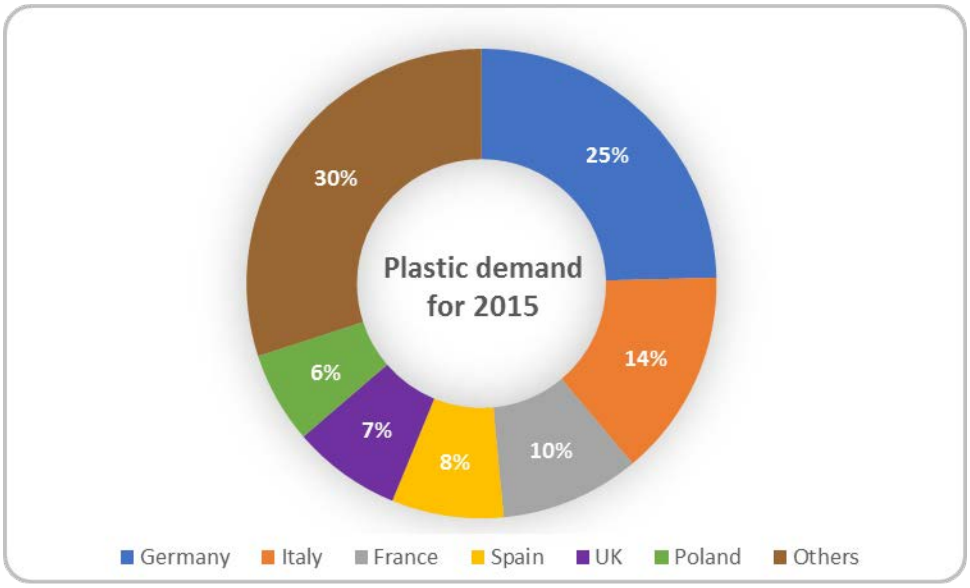

Figure 1: Plastic demand in Europe for 2015 (PlasticsEurope 2016)

An ambitious directive has set a "zero plastic to landfill" goal to be reached by 2025, reducing the landfill trend-line by 60 million tonnes, saving an equivalent amount of 750 million barrels of oil (PlasticsEurope 2016; Brems, Baeyens, and Dewil 2012). Marine pollution has recently been emphasised as one of the issues to account for in the Sustainable Development Goals in an attempt to secure "blue wealth". This is an imperious topic as these systems are being increasingly explored and marine policies are required, as well as planetary cooperation regarding a healthy ocean, that can continue to provide resources for a stable economy and general sustainability of the planet (Visbeck et al. 2014).

Nowadays, besides the issues regarding plastic safe disposal, a concerning matter is the occurrence of microplastics in the environment as reported in recent reviews of current trends and future perspectives in this matter (Barboza and Gimenez 2015; Shim and Thomposon 2015). Microplastics are small particles of plastic (diameter ≤ 5mm) which can have two different sources: primary, when they enter directly to the environment, mostly as raw material from the plastic industry or as micro-components present in cosmetic or hygiene products like toothpastes, shampoos, soaps or lotions (Cole et al. 2011); secondary, when they appear indirectly in the environment from the degradation of bigger plastic fractions due to the action of climatic conditions or physical elements, like sunlight or erosion (Andrady 2011). Whether they are directly flushed down sanitary facilities, or their parent compounds are unduly thrown to water courses being exposed to aggressive conditions that disintegrate them, microplastics become easily available to the existing wildlife, possibly causing death or harm through ingestion, entanglement, chemical pollution interactions or trophic transfer (Li, Tse, and Fok 2016; Ivar do Sul and Costa 2014; Wright, Thompson, and Galloway 2013; Sigler 2014). This effect is in an early stage of investigation but some authors have already characterized fractions of microplastics in sediments sampled in natural reserves exposing their polymer types and also their additive contents (Fries et al. 2013; Lozoya et al. 2016). Other works report possible scale-up effects reaching man through seafood (Van Cauwenberghe and Janssen 2014) and fishes (Rochman et al. 2015) intake. If fauna and flora threatening was not a sufficient reason to draw the attention of the legal authorities, this finding should set an alarm due to a possible impending catastrophe, which could reach several communities and generations around the world.

Two possible approaches to reduce microplastics formation are: to promote and implement the production and utilization of biodegradable plastics or to intervene in the waste management systems so that they can take in such noxious residues (Pettipas, Bernier, and Walker 2016). The first case is still seen as an ambiguous option as, besides starch and vegetable oils, some of the ecological formulations also include synthetic polymers (although in smaller portions, when compared to traditional plastic products), accounting for a reduced degradation time, but not to a total biodegradability (O'Brine and Thompson 2010; Müller, Townsend, and Matschullat 2012). More research is needed to achieve better options, and legislation that preconize these sustainable alternatives should be enforced so that they can gradually replace the existing ones. Meanwhile, waste management systems are being assessed under a dual perspective, reducing plastic residues at the source, *i.e.* before entering the environment, or as a clean-up strategy (Rochman 2016).

This work will focus on the second procedure, highlighting plastics as a valuable feedstock in the view of the waste to energy (WtE) methodologies, constituting a very promising means of creating highly claimed assets.

2. Methodology

A dedicated search for literature was conducted making use of the online resources available for the academic community of the Faculty of Engineering of the University of Porto, namely scientific databases like Web of Science, Scopus and Inspec, along with specific individual editorial webpages, in some cases. Foremost techniques were used in order to limit the existing literature and to manage references, further case-by-case assessment of the results being performed (Öchsner 2013) in an attempt to resume what has already been done and to establish a link between that and the less-explored possibilities that could be taken into account in the future.

3. Discussion

In this chapter, a brief description of the thermal conversion of residues will be steered, contextualizing the waste-to-energy process as well as emphasizing its major contributions to a more sustainable waste management system. Also, a possible option to lessen microplastics as environmental debris will be suggested, as a combination of the reviewed literature and the knowledge of the thermochemical conversion methods.

3.1. Waste-to-energy

Among other options such as recycling and composting, energetic valorization is one of the possible mechanisms through which waste streams may be treated. Thermochemical processes enable the recovery of energy from residues, consisting in a waste-to-energy (WtE) technique (Bosmans et al. 2013). The most common thermochemical methods are described in Table 1.

Pyrolysis consists in the thermal degradation of feedstocks at relatively low temperatures, affording three different product fractions: liquid, gas and solid. Besides the necessary pre-treatment this method involves, the obtained fractions require a final treatment to the achievement of energetically usable oils, and the simultaneous breakdown of the organic contents. Waste pyrolysis can afford several hundred different compounds, most of them considered useless or, worse than that contaminants, which can entail additional cleaning procedures (Bosmans et al. 2013). Incineration is the waste degradation through oxidation of the combustible species, giving rise to energy in the form of heat. This is accomplished in different stages, which can be controlled in order to reduce pollutant emissions such as furans and dioxins. Besides these compounds, fly and bottom ashes, dust and other residues are produced, gas cleaning equipment being mandatory, according to specific legislation (Bosmans et al. 2013).

Gasification is a thermochemical conversion scheme that converts carbonaceous materials into a synthetic gas (syngas), composed of carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen (Balat et al. 2009; Basu 2010). Sometimes using catalysts such as quartzite sand or Ni-based compounds promotes H_2 formation, while reducing methane (Ruoppolo et al. 2012) or even endorses smaller activation energies (Chin et al. 2014), enabling faster reactions and easier conversions. Catalysts like Ni-based, iron-based, calcined dolomites and magnesites, zeolites and olivine act *in situ*, advocating chemical reactions that alter syngas composition and heating value (Pinto et al. 2015).

Process	Pyrolysis	Incineration	Gasification
Temperature (^{o}C)	380-530	800-1300	500-1800
Pressure (MPa)	0.1-0.5	> 0.1	> 0.1
Pre-treatment	Necessary	Useful	Necessary
Catalyst	Not necessary	Not necessary	Useful

Table 1: Summary comparison for the major thermochemical conversion processes, adapted from Basu (2010)

As seen in Table 1, gasification depicts higher temperatures allowing a wider range of materials to be encompassed, and assuring a cleaner technology once nearly all the sub-products or contaminants will be precluded. Thus, gasification promotes efficient results for several kinds of residues, reducing waste amounts with the benefit of producing important assets like heat, electricity, fuels and chemicals (Bosmans et al. 2013; Lupa et al. 2011; Brems, Baeyens, and Dewil 2012; Arafat, Jijakli, and Ahsan 2015). It occurs through a sequence of interdependent events from drying to pyrolysis, oxidation and reduction being described by a set of reactions inside the gasification chamber (Li, Zhang, and Bi 2010; Basu 2010), as shown in Figure 2.

Numerous authors report gasification appliance to different debris, *e.g.* biomass (Ahmad et al. 2016; Brito, Oliveira, and Rodrigues 2014; Fremaux et al. 2015; Kuo and Wu 2015; Ogi et al. 2013; Sansaniwal et al. 2017; Wang et al. 2015), municipal solid wastes (Arena 2012; Couto et al. 2015a; Couto et al. 2015b; Hu et al. 2015; Wang et al. 2012) and even mixtures of diverse feedstocks (Lahijani et al. 2013; Kawamoto and Lu 2016; Đurišić-Mladenović, Škrbić, and Zabaniotou 2016; Akkache et al. 2016; Ong et al. 2015; Pinto et al. 2014; Zaccariello and Mastellone 2015; Zhu et al. 2015). Although there are several types of gasifiers (Arena 2012), these may be generally classified in three main categories according to some technical and operational features, as defined in Table 2. The choice of each particular gasifier depends on multiple factors such as the syngas quality required and the size of the feedstock particles, each of them featuring also different operational conditions and restrictions (Guell, Sandquist, and Sorum 2013; Arena 2012). In the case of biomass and wastes, fluidized beds are the most commonly used gasifiers as they tolerate a wider particle size range, which is crucial for this type of residues (Bosmans et al. 2013; van der Drift, van Doorn, and Vermeulen 2001; Siedlecki, de Jong, and Verkooijen 2011).

Oxidation Reaction

Volatiles

$CO + 1/2O_2 \leftrightarrow CO_2 \quad \Delta H = -283 kJ/mol$

$H_2 + 1/2O_2 \leftrightarrow H_2O \quad \Delta H = -242 kJ/mol$

Char

$C + 1/2O_2 \leftrightarrow CO \quad \Delta H = -111 kJ/mol$

$C + O_2 \leftrightarrow CO_2 \quad \Delta H = -394 kJ/mol$

Boudouard Reaction

$C + CO_2 \leftrightarrow 2CO \quad \Delta H = -172 kJ/mol$

Water-Gas Reaction

Primary

$C + H_2O \leftrightarrow CO + H_2 \quad \Delta H = -131 kJ/mol$

Secondary

$C + 2H_2O \leftrightarrow CO_2 + 2H_2 \quad \Delta H = -90 kJ/mol$

Methanation Reaction

$C + 2H_2 \leftrightarrow CH_4 \quad \Delta H = -75 kJ/mol$

Water-Gas Shift Reaction

$CO_2 + H_2 \leftrightarrow CO + H_2O \quad \Delta H = -41 kJ/mol$

Steam Reforming Reaction

$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \Delta H = 206 kJ/mol$

$$C_nH + nH_2O \leftrightarrow nCO + \frac{(n+m)}{2} H_2$$

Dry Reforming Reaction

$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \quad \Delta H = 247 kJ/mol$

$$C_nH_m + nCO_2 \leftrightarrow 2nCO + \frac{m}{2} H_2$$

Figure 2: Brief description of gasification reactions in the chamber

Gasifier Type	Sub-type	Temperature	Flows: Fuel	Flows: Oxidant	Remarks
Fixed Bed	Updraft	1000 ^oC	downward	upward	Simple and robust, fuel size and moisture content restrictions
	Downdraft		downward	downward	
Fluidized Bed	Bubbling	800-850 ^oC	upward	upward	Relatively low cost, ease of operation, good scale-up potential
	Circulating		upward	upward	
Entrained Bed	---	1200-1500 ^oC	downward	downward	Higher costs, complex, fuel size restrictions, suitable for high capacities

Table 2: General classification for gasifiers according to bed type and reactor flows

3.2. Microplastics gasification

As plastics can be disposed of in diverse shapes, sizes and from a multitude of origins (including microplastics), the comprehensive character that gasification has to offer confirms this technique as a valuable conversion method for these residues, as reported by several authors (Al-Salem, Lettieri, and Baeyens 2009; Arena, Zaccariello, and Mastellone 2009; Aznar et al. 2006; Baloch et al. 2016; Kim et al. 2011), some even suggesting a possible replacement of fossil fuels (Straka and Bičáková 2014).

Apart from the assets achieved from plastics gasification, improved results were obtained for mixtures of plastics with other residues, due to their valuable energetic composition that contributes to ameliorated process outcomes (Ahmed, Nipattummakul, and Gupta 2011; Moghadam et al. 2014; Yang et al. 2015; Alvarez et al. 2014). This was shown by Ahmed, Nipattummakul, and Gupta (2011), who observed enhanced syngas yield and composition as well as higher energy contents and thermal efficiency for mixed samples of woodchips and polyethylene (PE). The comparison of the enriched syngas to the expected composition if linear behaviour occurred is represented in Figure 3 and it can be seen that the results of co-gasification of the mixed samples are superior to the predictable values and also to the situations where the plastic residues or the biomass samples were gasified alone (0% PE and 100% PE, respectively). The explanation may rely on the hydrogen donor capacity of the plastic residues, which stabilizes the radicals generated from biomass and also, on the contribution of biomass char to the adsorption of volatiles from polyethylene, exalting hydrogen production.

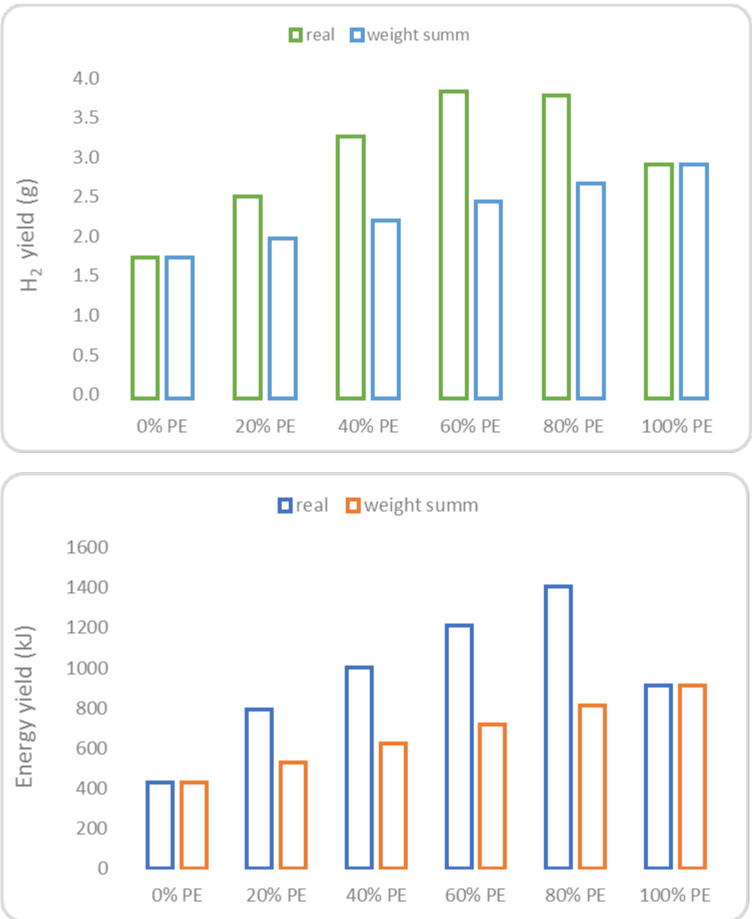

Figure 3: Synergistic effect of co-gasification of wood chips and polyethylene on hydrogen (top) and energy (bottom) yields, based on Ahmed, Nipattummakul, and Gupta (2011)

Moghadam et al. (2014) also reported upgraded syngas production and conversion rates when polyethylene ratio was raised in mixtures with palm kernel shell. This easier degradation was promoted by the higher volatile matter and lower ash contents of PE. Alvarez et al. (2014) investigated the addition of plastics to wood sawdust observing increased gaseous contents for higher plastic fractions as well. Yang et al. (2015) studied the gasification characteristics of rice straw (RS) with three different plastics (PE; polyethylene terephthalate - PET; polyvinyl chloride - PVC) and were able to find lower activation energies when compared to the weighted summation of the individual activation energies of the plastics and rice straw.

Figure 4 depicts a comparison of the activation energy obtained for the real samples to the projected for the linear addition of the weighted contribution of each fraction, synergistic effects between rice straw and all the plastic residues being registered, as can be seen from the lower activation energies achieved for real samples. This effect is more evident for PE than for PET or PVC, possibly due to its less bulky environment which enables faster reaction at high temperatures.

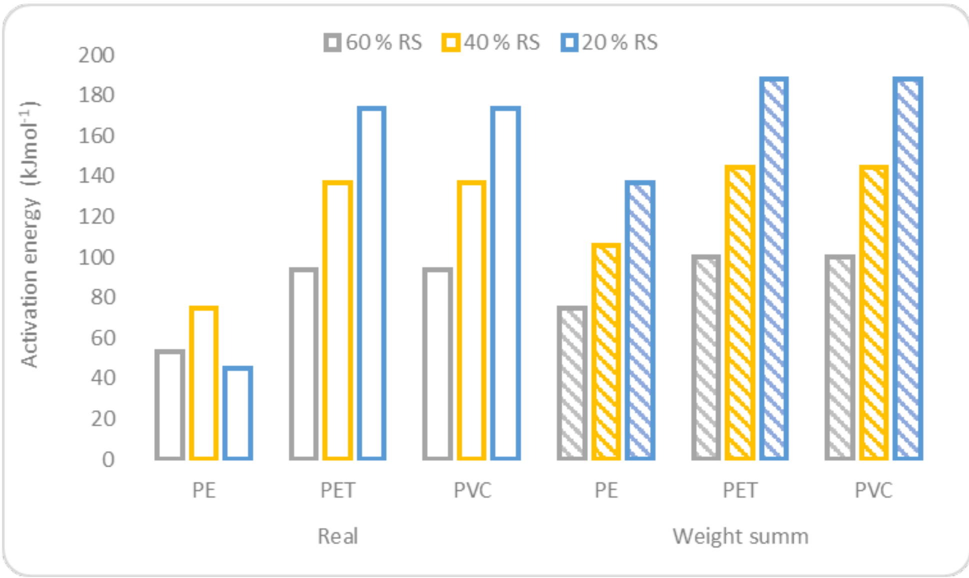

Figure 4: Synergistic effect of co-gasification of rice straw and different plastic residues, based on data from Yang et al. (2015)

Besides the benefits pointed hitherto, this synergetic effects boost gasification as a prominent technology especially in the case of plastic residues, taking advantage of their intrinsic properties to acquire upgraded results.

Referring to microplastics, to the best of the authors' knowledge there is only one published paper reviewing the microwave-induced plasma gasification (MIPG) of synthetic (and organic) waste polluting waterbodies (Panicker and Magid 2016). This work suggests the use of MIPG to clean rivers, lakes and even the ocean adapting the gasifier station to boats or platforms, so that waste is collected and conveyed to the reactor, the produced syngas being used to power the plant and the boat itself, among other commercial uses. Although this may seem complex or expensive to assemble and implement in a wide-range of countries and specific locations, gasification has indirectly shown to be adequate for microplastics as published in a manifold of papers that concern regular size-plastic residues, using pre-treatment steps such as shredding, pulverizing, sieving, grinding among others. All these actions reduce the particles size, which may be considered similar to using microplastics. In fact, reducing feedstock dimensions improves mass and heat transfer efficiencies due to larger surface areas and lower diffusion resistance coefficients, increasing reaction rates and fuel conversion (Hernández, Aranda-Almansa, and Bula 2010; Parthasarathy and Narayanan 2014). Figure 5 displays syngas composition and conversion rate for different particle sizes, a general decrease in both parameters being observed for bigger particles.

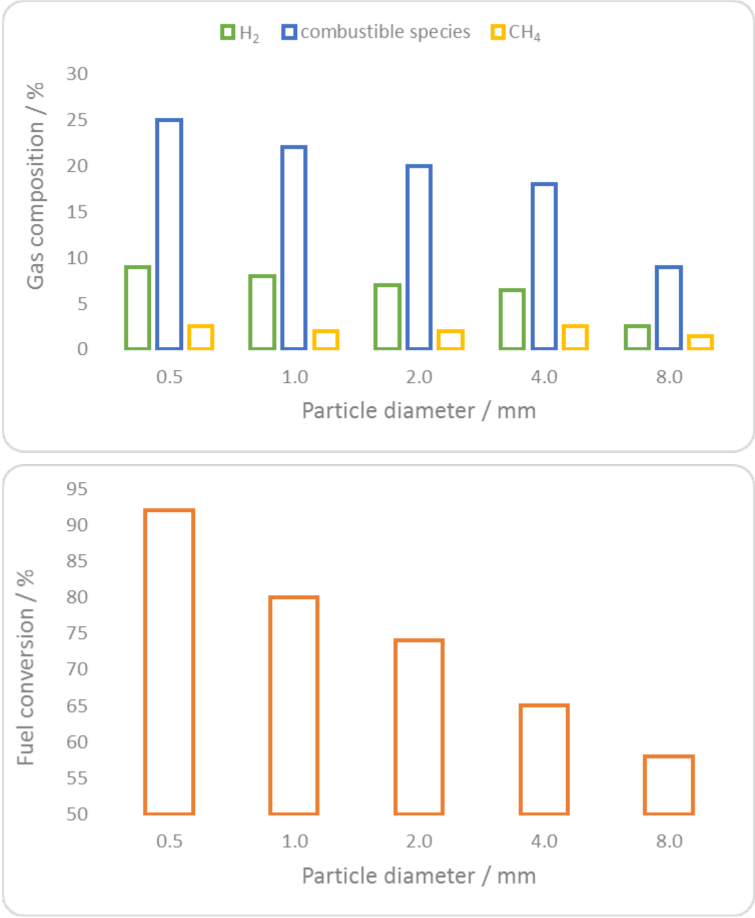

Figure 5: Effect of fuel particle size on syngas composition (top) and fuel conversion rate (bottom), based on Hernández, Aranda-Almansa, and Bula (2010)

Gasification reports of plastic residues that suffer a size reduction before the thermal conversion are widespread, some co-gasification examples clearly portraying the advantage of this step towards a more homogeneous feedstock (Chin et al. 2014; Lahijani et al. 2013; Moghadam et al. 2014).

4. Conclusions

This work aimed to potentiate gasification (and co-gasification) of (micro)plastics as an efficient and environmental-friendly method for treating this type of residues, aiding also to avoid their spread throughout the environmental compartments, in accordance to legislation and international recommendations. From the exposed, some findings could be highlighted helping to establish a logical sequence that can constitute a contribution to the aforementioned goal. WtE was presented as a dual-benefit method for turning environment more sustainable once it employs waste transforming it into energy and other assets, that become available for consumption without falling back on natural resources as fossil fuels do. From the major WtE techniques, gasification was shown to be the most suitable for plastic residues, namely fluidized beds have been reported as highly efficient reactors, due to their ability to comprise a vast range of feedstock dimensions. Several co-gasification reports on the interaction between plastic debris and other residues are published, revealing synergistic effects that promote enhanced results when compared to the single treatment of each of the fuels. Whereas gasification is strongly applied to regular plastic residues (bigger than microplastics) with excellent results, it demonstrates to be a favourable approach to the gasification of microplastics, as it commonly includes pre-treatment processes to reduce and homogenize feedstock dimensions, relevant evidences being stated in the case of co-gasification. This is also sustained by the fact that smaller particles endorse more effective interactions inside the gasification chamber, once phenomena like heat and mass transfer are better accomplished, preconizing higher reaction rates and improved microplastics conversion. Thus, gasification of microplastics should be regarded as a possible contributor to achieve the so called “blue wealth”, granting environmental and sustainable results in the reduction of marine, coastal or land based-polluted areas. Although numerous publications address gasification of plastic residues, more research is needed towards the implementation of this method in the specific case of microplastics *in situ*, as real conditions constitute a more tangible set of circumstances that can interfere with the global results. Therefore, the enforcement of technical measures that can embrace regional, national as well as international collaboration is highly required, so that the ocean’s impact on environmental degradation can regress as quickly as possible.

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