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Recent advances in the gasification of waste plastics. A critical overview

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A B S T R A C T

The current review provides an assessment of the main waste plastics valorization routes to produce syngas and H_2, thus covering different gasification strategies and other novel alternative processes, such as pyrolysis and in-line catalytic steam reforming. The studies dealing with plastics gasification are in general scarce. However, due to the knowledge acquired on biomass and coal gasification, the state of development of plastic gasification technologies is considerable and, in fact, several gasification studies have been performed at pilot scale units. Air gasification is the most studied and developed strategy and pursues the production of a syngas for energy purposes. In spite of the higher H_2 content and heating value of the gas produced by steam gasification, this alternative faces significant challenges, such as the energy requirements of the process and the tar content in the syngas. Moreover, the co-gasification of plastics with coal and biomass appears to be a promising valorization route due to the positive impact on process performance and greater process flexibility. Other promising alternative is the pyrolysis and in-line reforming, which allows producing a syngas with high hydrogen content and totally free of tar.

1. Introduction

Plastics have become a basic support for the modern style of living due to their low production cost and wide range of suitable properties, such as low density, durability and resistence to corrosion, and have therefore caused a displacement of traditional materials, such as wood, metals and ceramics [1]. In fact, plastics global production has steadily increased in recent years (Fig. 1), reaching a global annual production of 322 million tons (Mt) in 2015 [2].

The increase in plastics consumption corresponds to both the traditional plastics and the new plastic composites, with their main sectors of application being packaging, building, automotive, electrical and electronics, and agriculture [2]. Fig. 2a shows a detailed distribution of plastics demand in Europe according to the different sectors and Fig. 2b shows the distribution of the different plastic types. As observed, polyolefins account for half of the plastics produced, but polyvinyl chloride (PVC), polyurethane (PUR), polyethylene terephtalate (PET) and polystyrene (PS) are also produced in considerable amount.

Plastic waste management poses a great challenge that must be urgently addressed. Thus, the low degradability of the plastics causes serious environmental problems, especially in marine environments [3]. In addition, the inadequate management of waste plastics leads to sustainability problems due to the loss of valuable and scarce resources derived from petroleum. Accordingly, public policies have been promoted over the last years for improving waste plastics management. In fact, the fraction of waste plastics recycled and the one used for energy valorization in Europe over the last decade have increased by 64% and 46%, respectively, whereas the amount of waste plastics sent to landfill was reduced by 38% [2]. Although waste plastics management scenario is slowly improving in developed countries, its current situation is far from being satisfactory, and plastics management in developing countries is clearly less promising.

With the aim of reducing the amount of waste sent to landfill, different approaches are considered, namely, waste minimization, reuse, recycling and energy recovery. However, in the case of waste plastics, both minimization and reuse have been hardly applied [4]. Given their high calorific value, combustion is a feasible valorization route, but this alternative is hindered by the emissions produced [5]. Amongst recycling routes, chemical ones have the best perspectives for large scale implementation because they allow for the production of fuels, chemicals and syngas/hydrogen from waste plastics. The main chemical valorization routes of waste plastics are summarized in Fig. 3. Waste plastic pyrolysis is regarded as the main route for the production of fuels and chemicals from waste plastics [1,4,6–13]. In fact, different plastic pyrolysis processes aimed at the selective production of waxes [14–16], light olefins [17–21] and monomers [22,23] have been developed. Moreover, the co-pyrolysis of waste plastics and biomass is gaining increasing attention in recent years [10,24,25]. In spite of the interest in plastics pyrolysis process, its state of development and full-scale implementation is limited [6,10]. Furthermore, waste plastics or

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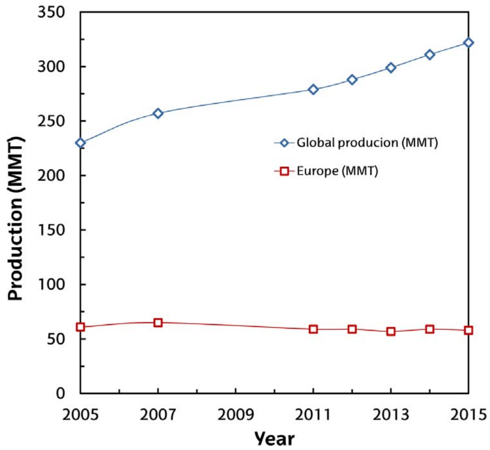

Fig. 1. Evolution of plastics global and European (EU-28) production during the last decade [2].

their derived products, such as pyrolysis waxes, may also be fed into conventional refinery units to produce fuels [10,26–28].

Gasification of waste plastics leads to the production of a stream made up of mainly H_2, CO, CO_2, CH_4 and N_2. Thus, the interest of gasification processes lies in the feasibility of producing energy, energy carries (such as H_2) and chemicals from the syngas produced (fuels, DME, methanol and so on) [29]. A remarkable advantage of gasification compared to pyrolysis is the greater flexibility to jointly valorize plastics of different composition or mixtures or plastics mixed with other feedstocks. The composition, and therefore applications, of the gas produced depends on the gasifying agent used. Thus, air gasification of waste plastics leads to a syngas with an average heating value in the 6–8 MJ m^{-3} range [30–33], with its main interest being energy production. Nevertheless, steam gasification allows for producing a N_2 free syngas with a heating value above 15 MJ m^{-3} [34,35], with its composition being suitable for synthesis applications. The main challenge of waste plastics gasification is the high tar content in the gas product, i.e., usually higher than those reported in biomass gasification [34,36–38]. Thus, a very efficient gas cleaning system is needed to meet the requirements for applying the syngas to chemical production [39–42].

Currently, the pyrolysis and in-line catalytic steam reforming [43–47] and the reforming of dissolved plastics [48–50] strategies are gaining growing attention. The interest of the pyrolysis-reforming process lies in the high H_2 production, usually above 30 g 100 $g_{plastic}^{-1}$ [45,46,51]. Moreover, the gaseous product obtained in the pyrolysis-reforming process is free of tars, and therefore they avoid the major problem involving gasification processes.

Therefore, this review analyses the state-of-the-art of the main waste plastic conversion technologies aimed at the production of syngas and H_2 including air gasification, steam gasification, co-gasification of plastics with other feedstocks, and pyrolysis-reforming. Thus, gasification and pyrolysis-reforming technologies are presented and their main features discussed. Moreover, their development state is critically evaluated and their scale-up possibilities assessed. The influence the

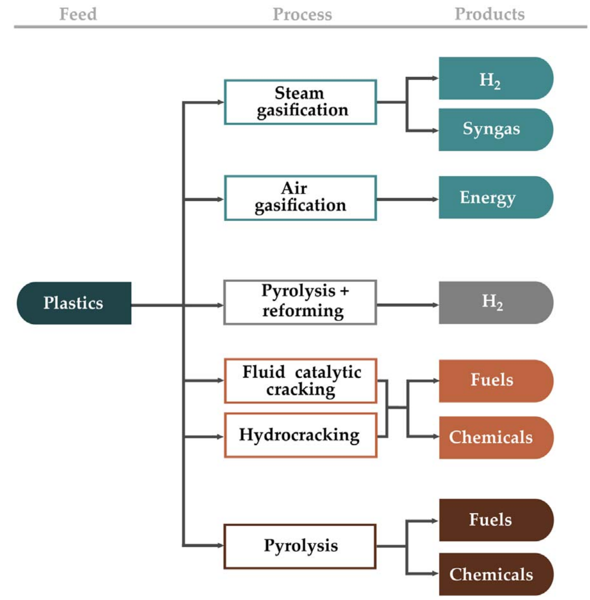

Fig. 3. Scheme of the main routes for chemical valorization of waste plastics.

main operating conditions have on conversion efficiency is evaluated, and so the role played by temperature, ER ratio, S/P (or S/C) ratio, feed composition and tar cracking or reforming catalysts is analyzed in depth. Moreover, focus is placed on key process parameters that allow assessing and comparing real process performance, such as the gas and H_2 productions and the quality of the syngas obtained (H_2 concentration, tar content, heating value and so on). Furthermore, the results obtained by the different valorization strategies have also been compared and their potential interest critically discussed.

2. Plastic waste management legislation

In spite of the great volume of waste plastics produced and the environmental problems associated with their inadequate handling, plastic waste management is not addressed by any specific EU legislation, but the Waste Framework Directive [52] and the Directive on Packaging and Packaging Waste [53] regulate their management.

In Europe, waste management was legislated for the first time in 1975 (Directive 75/442/EEC) with the aim of reducing waste production and its harmfulness [54]. This directive was modified throughout time [55] and currently waste management is legislated by the Waste Framework Directive 2008/98/EC [52]. Given that environment and human health protection are the main aims of this directive, the reduction of adverse impacts of waste generation and management is promoted, as well as the overall impacts involving the use of resources. The mentioned waste directive includes a waste management hierarchy, establishing the following priority order in waste prevention and management legislation and policy: i) prevention, ii) preparing for reuse; iii) recycling; iv) valorization; v) elimination. Besides, the Waste Framework Directive extended producer responsibility and marked the

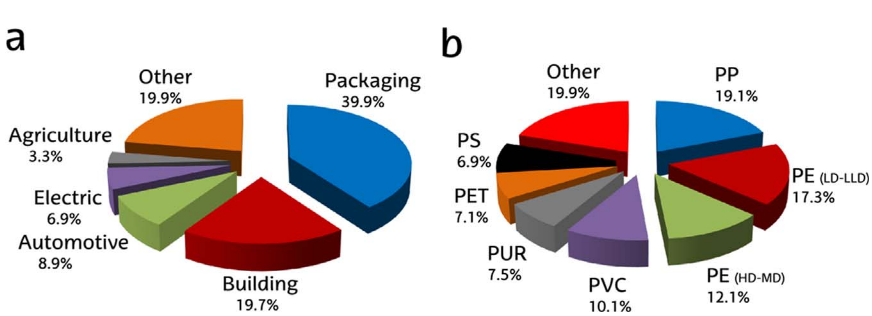

Fig. 2. Current plastic distribution demand in Europe according to their application (Fig. 1 a) and type of polymer (Fig. 1b) [2].