**INTRODUCTION**

According to the Secretary of the Environment (Naturales secretería de Medio Ambiente y Recursos, 2020), plastic waste is solid waste generated in homes or the industrial sector, which results in the elimination of materials used in its various activities such as containers, packaging, and packaging, among others.

Pyrolysis is a thermal process in which carbon-based compounds, including municipal solid waste (MSW), can be converted into combustible liquids at temperatures ranging from 300 to 600 °C or even higher. The process must be carried out in the total or partial absence of oxygen (O₂) (Rehan et al., 2016). The literary review shows various municipal wastes, such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS), and polypropylene (PP), which have been treated by thermal and catalytic pyrolysis to obtain fuel liquid (Ali et al., 2011; Cardona & Corma, 2000; Elordi et al., 1998; Kim & Kim, 2004; Lin et al., 2010; Miskolczi et al., 2009; Scott et al., 1990; Yoon et al., 1999). According to some researchers, the pyrolysis of PP, HDPE, LDPE, and PS can obtain liquid yields higher than 80%. On the other hand, the product shows characteristics very similar to commercial diesel; density (0.8 MJ/kg), viscosity (above 2.96 mm²/s), cloud point (-18 °C), flash point (30.5) and calorific value (40 MJ/kg)(Rehan et al., 2016). Therefore, the pyrolytic liquid has
the potential to be used as a fuel liquid for the generation of electrical energy, transport, and thermal machines (Kalargaris et al., 2017a, 2017b, 2018; Miskolczi et al., 2009; Ratio & Engine, 2021).

METHODS

Different types of plastic waste are found in municipal landfills (MPW), such as polystyrene, high-density polyethylene (HDPE), low-density polyethylene, polypropylene (PP), and mixtures, which have been successfully treated in recycling processes. Catalytic and non-catalytic pyrolysis. The operating conditions such as temperature, residence time, raw material, type of reactor, and composition have been reported and published by various authors.(Aisien et al., 2021; Ali et al., 2011; Anas et al., 2019; Eletta et al., 2017; Onwudili et al., 2009; Vijayakumar & Sebastian, 2018). The average higher calorific value (HHV) is 40 MJ/kg, and the average liquid fuel yield is within the 80% margin. (Sharma et al., 2014), with this, the potential for the generation of electrical energy for the next 20 years (2042) was estimated. Table 1 shows the heating values of some of the everyday plastics that can be commonly found in landfills.

According to the Ministry of the Environment and Natural Resources (SEMARNAT), the generation of municipal solid waste (MSW) in Mexico for the year 2022 was estimated at approximately 120,128 tons/day, which translates into an average of 0.944 kg/inhabitant/day within which 31.56% corresponds to waste that can be used, and of these, 7.66% refers to plastics and 1.55% to expanded polystyrene, that is, approximately 11,051 tons per day (Naturales secretaría de Medio Ambiente y Recursos, 2020). On the other hand, according to data obtained from the same SEMARNAT (Residuos Sólidos Urbanos (RSU) | Secretaría de Medio Ambiente y Recursos Naturales | Gobierno | Gob. Mx, n.d.) 83.93% is collected, and of this 78.54% ends up in final disposal sites, and only 9.63% of the total waste is recycled, it is expected

Table 1. High heating value (HHV) of some typical plastic waste

<table>
<thead>
<tr>
<th>Polymer (resin)</th>
<th>Calorific value (MJ kg⁻¹)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-density polyethylene (HDPE)</td>
<td>43</td>
<td>(Barbarias et al., 2018)</td>
</tr>
<tr>
<td>Polyethylene (PE)</td>
<td>43.3-46.5</td>
<td>(Al-Salem &amp; Lettieri, 2010)</td>
</tr>
<tr>
<td>Polypropylene (PP)</td>
<td>46.50</td>
<td>(Al-Salem &amp; Lettieri, 2010)</td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>41.90</td>
<td>(Al-Salem &amp; Lettieri, 2010)</td>
</tr>
<tr>
<td>Low-density polyethylene (LDPE)</td>
<td>46.6</td>
<td>(Qiao et al., 2018)</td>
</tr>
<tr>
<td>Expanded polystyrene (EPS)</td>
<td>41.29</td>
<td>(Huang et al., 2018)</td>
</tr>
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Figure 1. Projection in tons of solid waste (2012-2042)
that year after year the waste disposal will increase by an average of 2% (Figure 1).

The municipal solid wastes (MSW) were projected annually from 2022 to 2042, and according to this projection, they amount to more than 67 million tons (Figure 1). The benefits of landfill savings and electricity generation from liquid fuel and coal are considered. Landfill savings were calculated using a basic landfill cost of MXN 121.58 per ton of waste (Residuos Sólidos Urbanos (RSU) | Secretaría de Medio Ambiente y Recursos Naturales | Gobierno | Gob.Mx, n.d.). Electricity savings were calculated based on the typical price of MXN 0.75 per kWh and GHG emissions were calculated using the method proposed by the Intergovernmental Panel on Climate Change (IPPC). The method is described by Equation 1.

\[
Q = (M_{SWT} \times M_{SWF} \times M_{CF} \times D_{OC} \times D_{OCF} \times F \times 16 \div 12) (1 - O_X)
\]

where: \( Q \) – the total CH\(_4\) emissions (ton/year); \( M_{SWT} \) – the total MSW generated per year (ton/year); \( M_{SWF} \) – the fraction of solids disposed of in landfills; \( M_{CF} \) – a correction factor for methane; \( D_{OC} \) – the degradable carbon fraction; \( D_{OCF} \) – the dissimilated organic fraction; \( F \) – the gaseous fraction of CH\(_4\) in landfills; \( 16/12 \) – the molecular weight ratio of methane to carbon; \( O_X \) – an oxidation factor.

The details of Equation 1 estimate the emission profiles for methane (CH\(_4\)) and Mt.CO2 eq. Global warming potential (GWP) has been studied previously and can be consulted in the IPCC guidelines (Reay et al., 2007). The value of carbon is 23.20 US$ per ton of CO\(_2\) equivalent is considered for GHC emission savings (Rehan et al., 2016).

The electrical energy potential was calculated using Equation 2, where \( P_{MSW} \) is the electrical potential that can be generated through the pyrolysis of urban plastic waste (GW), MSW is the total urban solid waste generated annually (kg/year), FMSW is a factor that indicates the percentage of solid waste that can be recovered energetically, HHV is the higher calorific power that the plastics that can be recovered contain on average (MJ/kg), FLF is a factor that indicates the fuel liquid yield that can be can recover, \( t_A \) is the annual time (s).

\[
P_{MSW} = \frac{M_{SW} \times F_{MSW} \times H_{HV} \times F_{LF}}{t_A} \times (10^{-9}) \quad (2)
\]

RESULTS AND DISCUSSIONS

According to the projection of municipal solid waste that can be used, by the year 2022, there would be an estimated 45.6 million tons of plastic, which means a potential of 36.48 million tons of liquid fuel, increasing to 54.48 MT in 2042, with a high calorific value of 40 MJ/kg, which translates into a tremendous electrical energy potential of approximately 46.25 GW, with an increase of 2% each year (Figure 2), that is, a

![Figure 2. Electricity generation capacity through pyrolytic technology using all the plastic waste generated in Mexico](image-url)
potential of 126.71 MW/day, which can be used to power about 23,038 homes on average (average consumption of 5.5 kW/day).

The economic benefits for savings in fun landfills, electricity generation, and carbon credits tend to be approximately 1,574,622,866.63 US$ with an annual increase of 2%, generating significant economic savings (Figure 3). The Table 2 describes the technical details, economic evaluation, and implementation technique of a pyrolytic technology plant.

The liquid produced from the pyrolysis of plastic waste also offers the opportunity to be refined and distilled through refining plants, creating alternative fuels for electricity generation or transportation, fuel applications (Demirbas, 2004). In addition, the carbon produced through some chemical modifications can be used in water treatment plants or air purifiers, creating beneficial environmental impacts.

The most significant benefit is the reduction of GHG emissions, contributing to the reduction of greenhouse gases and benefiting society and the environment since this would help reduce the high rates of climate change. In addition, the savings generated from the pyrolysis of MSW can help develop underdeveloped communities by creating direct jobs for the surrounding area and, in turn, increasing the quality of life in these areas.

On the other hand, it should be emphasized that some areas used for waste disposal can be recovered, benefiting the surrounding fauna, and creating green spaces for the different species.

### Table 2. Technical, environmental, and economic evaluation of pyrolytic technology

<table>
<thead>
<tr>
<th>Technical details</th>
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<tbody>
<tr>
<td>Adequate waste</td>
<td>MPW, biomass</td>
</tr>
<tr>
<td>technology complexity</td>
<td>high</td>
</tr>
<tr>
<td>Skill required by staff</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Geographic location</td>
<td>industrial/urban area</td>
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<table>
<thead>
<tr>
<th>Environmental evaluation</th>
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<tbody>
<tr>
<td>CH4 potential emissions (ton/year)</td>
<td>2,237,871.22</td>
</tr>
<tr>
<td>GWP (Mt.CO2 eq.)</td>
<td>55,946,780.5</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Economic evaluation</th>
<th></th>
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<tbody>
<tr>
<td>Capital cost (ton/year)a</td>
<td>$17-$25</td>
</tr>
<tr>
<td>Operational cost (ton/year)</td>
<td>$23</td>
</tr>
<tr>
<td>Revenue from carbon credits(^b)</td>
<td>$1,297,965,307.52(^d)</td>
</tr>
<tr>
<td>Saving from landfill fun</td>
<td>$276,655,824.80(^d)</td>
</tr>
<tr>
<td>Saving from electricity generation</td>
<td>$1,734.31(^d)</td>
</tr>
<tr>
<td>Net revenue</td>
<td>$1,574,622,866.63(^d)</td>
</tr>
</tbody>
</table>

**Note:** aAccording to Rehan et al., [two]; bBased on GWP of 25 for methane; cAt a cost of US$ 23.20/tonnes of CO\(_2\); dthese values are based on 2022 and increase with approximately 2% (Figure 3).

![Figure 3. Potential savings in millions of US$ from landfill diversion, electricity generation by liquid fuel, and carbon credits from 2022 to 2042](image-url)
CONCLUSIONS

The potential of recycling MSW through pyrolysis as an alternative technology in Mexico has been analyzed. The pyrolytic liquid generated from the thermochemical degradation of the waste shows a high energy potential, on average, an HHV of 40 MJ/kg. On the other hand, the liquid fuel shows similar properties to diesel, such as density (0.8 kg/m³), viscosity (on average 2.96 mm²/s), cloud point (-18 °C), flash point (30.5 °C) (Balat, 2008; Kalargaris et al., 2017a; Sharma et al., 2014; Singh et al., 2019). The MSW generated in Mexico for the year 2022 is approximately 45.6 million tons with a projection of 67.1 million tons for 2042, for which the potential for electric power generation would increase proportionally, supplying approximately 23,038 homes. The most crucial part that should be emphasized is the economic savings for landfill diversion, revenue for carbon credits, and electricity generation, which amount to 1,574,622,866.6 US$ with an annual increase of 2%. As observed, the pyrolysis of MSW offers excellent economic, social, and environmental benefits. However, before opting for the implementation of plants, environmental impact studies must be carried out.

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REFERENCES


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