Technological Surveillance of Post-Consumer Polystyrene Pyrolysis as a Source of Non-Conventional Energy in Colombia

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Abstract
This document proposes a potential energy recovery process of polystyrene solid waste through the pyrolysis process for the city of Bucaramanga in Colombia through a documentary review. In addition, a comparison of the conditions of the processes used and characteristics of the products obtained is presented. For the development of this document, some sources of information were selected only from articles of indexed scientific journals in an interval of years from 2015 to 2020 analyzing the information collected in a descriptive and explanatory way, having a qualitative and quantitative level of measurement. It was obtained as a result the proposal of a microwave-mediated pyrolytic process without the use of catalysts, in a time between 5 to 15 minutes and a temperature between 450 to 500 °C, allowing to obtain, in several cases, a pyrolytic oil product with characteristics like those of conventional diesel fuel.

Keywords:Pyrolytic oil, Thermal utilization, Polystyrene, Pyrolysis, Solid waste.

1. Introduction

The population growth projection estimates that by the year 2030 there will be approximately 8 billion people; considering this, it is clear to recognize that in the same way there will be an increase in the number of necessary resources to fulfill basic needs, proportionally increasing the generation of solid waste (SW) [1].

According to the above, analyzing the generation of polymeric type SR (production that reaches an approximate increase of 300 million tons per year), specifically single-use polymers, which currently have a low level of recycling in addition to a long natural degradation time, poses a challenge in terms of mitigating environmental impacts derived from this type of SR, in most cases, caused by inadequate management in their disposal at the end of their useful life [2, 3].

Considering the number of single-use polymer types, this study focuses on polystyrene (PS) RS (Figure 1) which is one of the most widely used for packaging and packing activities due to its multiple physical and chemical properties. However, the utilization rate is lower in this polymeric RS compared to other types [4, 5].

Fig. 1. Polystyrene (PS)

Considering the inefficiency in the management for the treatment of this RS, it is important to highlight that it will lead to the proliferation of disease vectors, as well as impacts caused on the air resource related to offensive odors, emission of greenhouse gases (GHG), among others, increasing the problem associated to climate change [6, 7]. In addition, this directly contaminates resources such as soil and water because of the low degradation of this material, including alterations in the trophic chain [8, 9] among other aspects.

Although PS has been recycled through chemical modification for various energy applications, specifically as a sacrificial agent for enhanced crude oil recovery (Figure 2a) [10] and as a useful agent in carbon dioxide capture in post-combustion systems (Figure 2b) [11], direct energy utilization represents a promising additional use for this waste due to the need not only to improve SR management but also to obtain alternative energy sources [12].

Fig. 2. PS chemical recycled products (a) Sulfonated polystyrene (b) Polyamino styrene

Another way of using PS SR focuses on the energy recovery of the material, since this type of polymer has a calorific value similar to that contained in fossil fuels [13]. Regarding to this, processes such as incineration, gasification and pyrolysis are considered to be useful to close the life cycle of this material [14]. However, the incineration process in general, regardless of the SR to be treated, has disadvantages specifically because of the harmful atmospheric emissions that it can generate [15]. On the other hand, only the gas generated from the gasification process can present an additional utility, considering that the production of hydrogen cyanide and nitrogen dioxide is presented as a disadvantage [15].

Considering the above, the pyrolysis process is inclined as one of the best options for the energetic use of this type of waste, since it allows obtaining different materials (solid, gaseous, and liquid) that can have a wider spectrum of energy application [13, 15, 16].

For these reasons, it is necessary to conduct a technology watch on the progress of the transformation of PS waste into energy through the pyrolysis process as an alternative in the generation of non-conventional energy [17] for the city of Bucaramanga in Colombia, taking into account the economic and environmental benefits derived from the generation of liquid oil from this polymer and potential value-added products such as coal and gases [2, 18].

2. Literature Review

2.1. PS as SW in Colombia

According to Superintendencia de Servicios Públicos Domiciliarios (SSPD), an average of 11.6 % of plastic waste is generated in Colombia [19]; a value that becomes relevant when it is known that, on average, during a day a total of approximately 31406 tons of RS are disposed of in the different disposal sites for which information is available [20]. In this regard, the total average amount of daily tons of plastic RS would be 3643. Considering the above, if the generation of PS MSW in an average city is considered with a value of 16.6% [21], the specific generation of this type of MSW would be 604,754 tons per day at the national level and specifically in Bucaramanga, this value would reach 92,510 tons per day [20].

2.2. Analysis of Colombian regulations focused on the use of non-conventional energy sources.

Colombia has an important potential for energy generation with the help of projects from non-conventional sources and due to the responsibility acquired in the face of climate change. The country's energy policy has been aimed at optimizing the sustainable development of the sector. With Law 1715 of 2014 which was amended and updated by Law 2099 of 2021, according to the Colombian Congress (2021) international agreements obtained by Colombia in terms of demand management and renewable energies that were complied with.

Law 2099 of 2021 establishes an advance for the contribution of sustainability in Colombia, with it the efficient use of resources and care for the environment is encouraged and includes a structure of alternative solutions and incorporation of sites in the country that currently do not have access to electric power service. The law also provides for utilities of public and social interest for the promotion and development of non-conventional energy sources. Through this regulation, several tax incentives are granted to those who invest in the research, production and development of projects focused on non-conventional energy sources. This law regulates matters related to the exploration and research of geothermal resources, creates a geothermal registry, and provides certain penalties for those who fail to comply with the provisions regulating the exploration and exploitation of this resource.

The tax reduction is an incentive to favor investment in renewable energies in Colombia, a very important issue, considering the expenses that must be made each year to the treasury for the projects and investments that are made.

2.3. General information about the pyrolysis process.

Taking into account the energy potential that RS matrices can represent globally, it is important to review the generalities of the pyrolysis process for the conversion of these (RS) into non-conventional energy sources, perhaps even fulfilling the needs of communities that do not have enough supply from the general energy supply network, directly impacting some of the goals proposed for goal 7 of the Sustainable Development Goals (SDGs), which seeks to ensure access to affordable, reliable, sustainable and modern energy for all [22].

Based on the above, the pyrolysis process focuses on the decomposition or thermochemical conversion of any organic substance by increasing the temperature in the absence of oxygen, obtaining mainly syngas, char, and oil as by-products of the process, in proportions and purities that will depend mainly on the raw material and the various conditions that the process may have [23].

Referring to the process conditions, the temperature and heating rate of the reactor, gives rise to a classification in the pyrolysis process, having fast and slow pyrolysis, as the only difference during the process, the speed in the reactor heating rate. However, the difference in heating rate can give rise to products such as syngas and oil (fast process) and char (slow process) [24].

Alternatively, the literature proposes the use of co-pyrolysis to improve the yield of obtaining liquid fuels by using biomass in addition to PS, highlighting the use of microwave-assisted reactors in which microwave-induced plasmas or materials that absorb microwaves are used, directly influencing the reaction time required to obtain by-products of interest [13].

2.4. Process parameters

Some authors over time have extensively reviewed pyrolysis process parameters, even for PS waste, however, it is fair to mention that, taking into account the technological scope of Colombia, it is convenient to review basic parameters for a process that does not demand a high number of economic resources. Regarding to this, this document will include parameters such as temperature, batch, fixed and fluidized bed reactors, microwave-assisted pyrolysis, and catalytic pyrolysis.

2.4.1. Temperature

This is one of the most important parameters for the pyrolysis process of RS of PS, since it is the parameter that allows the fractionation of the polymeric chain of PS, in addition, it has been reported that this polymer is the one that presents a lower degradation temperature, for this reason, research has reported that temperature is the parameter with the highest incidence in obtaining various by-products, because if the desired product is to be gaseous or solid (carbon), the temperature should be higher than 500 °C, on the other hand, if the desired product is oil, the obtaining temperatures will be in lower ranges, between 300 and 500 °C [13].

2.4.2. Reactors

The type of reactor to be used for PS utilization has a direct influence on the efficiency of mixing PS with catalysts, residence times, heat transfer rates and even the efficiency in obtaining the desired by-products. In the literature there are several types of reactors that respond to a variety of by-products obtained and even to certain characteristics such as obtaining efficiency. For this, there are reports of batch reactors used with polymer blends in which PS is included [25], in co-pyrolysis processes with diverse presence of biomass [26, 27], and used only with PS [28–30]. Additionally, fixed-bed reactors [31–36] used for PS waste treatment have been reported.

The literature also reports the use of microwave ovens for the pyrolysis process of RS of PS, highlighting the need for short residence time of the residue inside the oven, the reach of high temperatures in short times and the possibility of using them in conjunction with catalysts such as CaO to improve the yield of obtaining pyrolytic oil [23, 27, 37].

2.5. Properties of pyrolytic PS oil

According to the information reported, specifically from those studies that performed an energetic characterization of the liquid product of the pyrolysis process carried out on PS under different configurations (Table 1), it has been shown that the co-pyrolysis process allows a higher yield of oil to be obtained, in addition to properties very similar to those of liquid fuels such as diesel or gasoline.

Table 1. Characterization of pyrolytic oils obtained from PS

CARACTERISTICS											REFERENCES
REACTION CONDITIONS						**PYROLYTIC OIL PROPERTIES**					
Raw Material	Pol:Bio	Reactor	Furnance power (kW)	Time (min)	Temperature (ºC)	Yield (%)	Calorific value (MJ/kg)	Kinematic Viscosity (cSt)	Density (g/cm^3)	Flash point (°C)	
PS + coal from tires	76:24:00	Microwave oven	3	30	574	87,50	-	-	0,92	-	[37]
PS + silicon carbide	67:33:00	Microwave oven	3	91	574	85,00	-	-	0,92	-	
PS + karanja	1:01	Semi-discontinuous	N/A	-	550	78,25	38,83	-	0,90	-	[38]
PS + niger	1:01	Semi-discontinuous	N/A	-	550	75,96	32,15	-	0,89	-	
PS	N/A	Discontinuous	N/A	75	450	80,80	41,6	1,92	0,92	30,2	[28]
PS	N/A	Fixed bed	N/A	30	500	72,08	43,94	-	0,86	-	[31]
PS	N/A	Discontinuous	N/A	70	300	80,00	-	1,46	0,88	-	[29]
PS + activated carbon	10:01	Discontinuous	N/A	60	418	82,98	44	2,40	0,92	-	[26]
PS + activated carbon	10:01	Microwave oven	0,45	5,5	330	93,04	45	2,73	0,90	-	
PS + mixed wood sawdust		Microwave oven	0,45	10-11,5	600	59,40	39,20	-	1,12	-	[27]

CARACTERISTICS											REFERENCES
REACTION CONDITIONS						**PYROLYTIC OIL PROPERTIES**					
Raw Material	Pol:Bio	Reactor	Furnance power (kW)	Time (min)	Temperature (ºC)	Yield (%)	Calorific value (MJ/kg)	Kinematic Viscosity (cSt)	Density (g/cm^3)	Flash point (°C)	
PS	N/A	Pyrex	N/A	70	410	85,00	-	1,71	0,83	-	[39]
PS + wheat straw	N/A	Discontinuous fixed bed	N/A	30	550	55,00	40,58	2,96	0,89	19	[34]
PS + corn stalk	3:01	Fixed bed	N/A	30	550	68,00	41,80	4,56	0,90	23	[33]
PS	N/A	Screw conveyor and fluidized bed	N/A	-	297 y 694	94,83	40,89	0,97	0,95	79	[40]
PS + PP + rice husk activated carbon	10:01	Microwave oven	0,9	2	450-500	69,55	46,87	2,13	0,75	-	[23]
PS + PP + coconut pod activated carbon	10:01	Microwave oven	0,9	3	450-500	84,30	46,83	2,49	0,76	-	
PS + PP + corn husk activated carbon	10:01	Microwave oven	0,9	3,5	450-500	77,40	46,81	2,45	0,76	-	

CARACTERISTICS												REFERENCES
REACTION CONDITIONS						**PYROLYTIC OIL PROPERTIES**						
Raw Material	Pol:Bio	Reactor	Furnance power (kW)	Time (min)	Temperature (ºC)	Yield (%)	Calorific value (MJ/kg)	Kinematic Viscosity (cSt)	Density (g/cm^3)	Flash point (°C)		
PS + PP + activated carbon	10:01	Microwave oven	0,9	2	450-500	59,05	46,32	2,23	0,79	-		
GASOLINE							**42-46**	**1,1-7**	**0,72-0,78**	**43**		[2]
DIESEL							**42-45**	**2-5,5**	**0,81-0,87**	**53-80**		

From the tabulated information, it is possible to highlight the wide use that has been made of microwave ovens for the pyrolysis process of polymeric SR, specifically those that are sometimes considered non-recyclable, as it's the case of PS.

3. Discussion

Taking into account the amount of polymeric RS that reach the landfill in the region, and the little use that is made of them, it is necessary to make a proposal for the use of PS waste (which is a waste that reaches the landfill in 16.6% of the total polymeric RS) [21], in order to contribute to reduce the environmental problem of RS that is experienced in the region.

Initially, to propose the utilization proposal, properties such as the calorific value and viscosity of the oil obtained were considered, since these are very important characteristics of the fuels. By obtaining a calorific value close to that of conventional fuels in the different studies reviewed, it is possible to demonstrate that pyrolytic oil could replace fossil fuels obtained from conventional sources (oil, coal, gas) to a certain extent, and it is also important to mention that those fuels with a higher calorific value will be needed in smaller quantities to perform the same function as fuels with a lower calorific value; as for viscosity, those fuels with lower viscosity have greater advantages in relation to injector leakage and potential loss of the injection pump at the time of application to the engine [28, 41].

Finally, the implementation of the pyrolysis process to produce a low-cost fuel with a possible usable energy potential [23], using a microwave oven as a reactor, since this accelerates the process reaction and needs less time than other conventional reactors [23, 26]. Additionally, it is proposed not to use any type of catalyst, because although it was evidenced in some studies the use of some catalysts that improve the yield of the liquid product, it was not possible to know the properties or characteristics of this product. The reaction conditions would be approximately with a time between 5 to 15 minutes and a temperature between 450 and 500 ºC, achieving pyrolytic oils with approximately a yield percentage of 80 to 90%, a calorific value between 44 and 45 MJ/kg, a kinematic viscosity between 2.4 to 2.8 cSt, a density between 0.75 to 0.90 g/cm3; which are properties that present some similarity with diesel as a conventional fuel [42]. It should be noted that, apart from PS as raw material, biomass such as activated carbon or coconut husk carbon can be added to the process to improve its efficiency, since carbon helps the decomposition of polymeric residues during microwave oven irradiation [23].

4. Conclusions

The use of PS residues with the pyrolysis process allows obtaining liquid, gaseous and solid products; however, greater profit or percentage of yield is obtained with the liquid product, which can become an interesting alternative to replace fossil fuels. Additionally, the microwave oven was recognized as the best reactor for the pyrolysis process of PS according to the studies analyzed, since it greatly reduces the time and temperature of the process as opposed to conventional reactors, in addition to obtaining liquid products with good efficiency.

The pyrolytic oil obtained from the pyrolysis process of PS with its respective optimal reaction conditions in microwave ovens, is inclined to be a possible alternative for the city of Bucaramanga in Colombia, as it is an oil with a strong potential, properties and/or characteristics like those of conventional diesel fuel, and can be used as a non-conventional alternative energy source, contributing to the solution of the current environmental problem of SW..

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References

[1] S. Nanda and F. Berruti, A technical review of bioenergy and resource recovery from municipal solid waste. J. Hazard. Mater., vol. 403, 123970, 2021., 2020.

[2] K. Kumar Jha and T. T. M. Kannan. Recycling of plastic waste into fuel by pyrolysis - a review. Mater. Today Proc., vol. 37, pp. 3718–3720, 2021.

[3] W. Zhang, Z. Liu, S. Tang, D. Li, Q. Jiang, and T. Zhang. Transcriptional response provides insights into the effect of chronic polystyrene nanoplastic exposure on Daphnia pulex. Chemosphere, vol. 238, pp. 1–9, 2020.

[4] M. H. Al-Mashhadani et al. Environmental and morphological behavior of polystyrene films containing Schiff base moiety. Mater. Today Proc., vol. 42, pp. 2693–2699, 2021.

[5] Y. S. Jeong, J. W. Kim, M. W. Seo, T. Y. Mun, and J. S. Kim. Characteristics of two-stage air gasification of polystyrene with active carbon as a tar removal agent. Energy, vol. 219, p. 119681, 2021.

[6] M. A. Hannan, M. Akhtar, R. A. Begum, H. Basri, A. Hussain, and E. Scavino. Capacitated vehicle-routing problem model for scheduled solid waste collection and route optimization using PSO algorithm. Waste Manag., vol. 71, pp. 31–41, Jan. 2018, doi: 10.1016/j.wasman.2017.10.019.

A. Singh. Managing the uncertainty problems of municipal solid waste disposal. J. Environ. Manage., vol. 240, pp. 259–265, Jun. 2019, doi: 10.1016/j.jenvman.2019.03.025.

[7] G. E. De-la-Torre, D. C. Dioses-Salinas, C. I. Pizarro-Ortega, and L. Santillán. New plastic formations in the Anthropocene. Sci. Total Environ., vol. 754, p. 142216, Feb. 2021, doi: 10.1016/j.scitotenv.2020.142216.

[8] Y. Mukai, A. Goto, Y. Tashiro, S. Tanabe, and T. Kunisue. Coastal biomonitoring survey on persistent organic pollutants using oysters (*Saccostrea mordax*) from Okinawa, Japan: Geographical distribution and polystyrene foam as a potential source of hexabromocyclododecanes. Sci. Total Environ., vol. 739, p. 140049, Oct. 2020, doi: 10.1016/j.scitotenv.2020.140049.

[9] D. R. Merchan-Arenas, A. F. Murcia-Patiño, L. E. Cortés-Castillo, and V. V Kouznetsov. Sulfonation of Expanded Polystyrene Post Consumption, Structural Analysis and Its Application in Chemical Enhanced Oil Recovery. Chem. Eng. Trans., vol. 57, pp. 631–636, 2017.

[10] D. R. Merchán-Arenas and A. F. Murcia-Patiño. Synthesis of polyamino styrene from post-consumption expanded polystyrene and analysis of its CO_2 scavenger capacity. Int. J. Environ. Sci. Technol., vol. 18, no. 9, pp. 2519–2532, Sep. 2021, doi: 10.1007/s13762-020-03009-z.

[11] T. Lee et al. Catalytic Pyrolysis of Polystyrene over Steel Slag under CO2 Environment. J. Hazard. Mater., vol. 395, p. 122576, Aug. 2020, doi: 10.1016/j.jhazmat.2020.122576.

[12] Maafa. Pyrolysis of Polystyrene Waste: A Review. Polymers (Basel)., vol. 13, no. 2, p. 225, Jan. 2021, doi: 10.3390/polym13020225.

[13] S.-J. Cho et al. Study on Incineration/ Pyrolysis/ Gasification Characteristics of Urethane/ Styrofoam Generated from Home Appliances Waste. 2010.

[14] Kemona and M. Piotrowska. Polyurethane Recycling and Disposal: Methods and Prospects. Polymers (Basel)., vol. 12, no. 8, p. 1752, Aug. 2020, doi: 10.3390/polym12081752.

[15] M. Bhatt et al. Valorization of solid waste using advanced thermo-chemical process: A review. J. Environ. Chem. Eng., vol. 9, no. 4, p. 105434, Aug. 2021, doi: 10.1016/j.jece.2021.105434.

[16] F. Abnisa and W. M. A. Wan Daud. A review on co-pyrolysis of biomass: An optional technique to obtain a high-grade pyrolysis oil. Energy Convers. Manag., vol. 87, pp. 71–85, Nov. 2014.

[17] Q. Hu, Z. Tang, D. Yao, H. Yang, J. Shao, and H. Chen. Thermal behavior, kinetics and gas evolution characteristics for the co-pyrolysis of real-world plastic and tyre wastes. J. Clean. Prod., vol. 260, p. 121102, Jul. 2020.

[18] INERCO Consultoría Colombia. VALORIZACIÓN ENERGÉTICA DE RESIDUOS: PROYECTO WTE COLOMBIA. Bogotá D.C., 2018.

[19] Superintendencia de Servicios Públicos Domiciliarios and Departamento Nacional de Planeación. Informe de Disposición Final de Residuos Sólidos – 2018. Bogotá D.C., 2019.

[20] Concejo Municipal de Bucaramanga. Proyecto de Acuerdo N° 008/2020. Por medio del cual se establecen medidas para restringir los plásticos de un sólo uso en la contratación pública del municipio de Bucaramanga y se dictan medidas para promover prácticas ambientalmente responsables. Anailable from https://www.concejodebucaramanga.gov.co/proyectos2020/PROYECTO_DE_ACUERDO_008.pdf, Colombia, pp. 1–13, Feb. 06, 2020.
[21] United Nations. Sustainable Development Goals. Ensure access to affordable, reliable, sustainable and modern energy.
[22] P. Rex, I. P. Masilamani, and L. R. Miranda. Microwave pyrolysis of polystyrene and polypropylene mixtures using different activated carbon from biomass. J. Energy Inst., vol. 93, no. 5, pp. 1819–1832, Oct. 2020, doi: 10.1016/j.joei.2020.03.013.
[23] C. De Blasio and M. Järvinen. Supercritical Water Gasification of Biomass. in Encyclopedia of Sustainable Technologies, Elsevier, 2017, pp. 171–195. doi: 10.1016/B978-0-12-409548-9.10098-3.
[24] R. Miandad, M. A. Barakat, M. Rehan, A. S. Aburiazaiza, I. M. I. Ismail, and A. S. Nizami, Plastic waste to liquid oil through catalytic pyrolysis using natural and synthetic zeolite catalysts. Waste Manag., vol. 69, pp. 66–78, Nov. 2017, doi: 10.1016/j.wasman.2017.08.032.
[25] R. Prathiba, M. Shruthi, and L. R. Miranda. Pyrolysis of polystyrene waste in the presence of activated carbon in conventional and microwave heating using modified thermocouple. Waste Manag., vol. 76, pp. 528–536, Jun. 2018, doi: 10.1016/j.wasman.2018.03.029.
[26] D. V. Suriapparao, B. Boruah, D. Raja, and R. Vinu. Microwave assisted co-pyrolysis of biomasses with polypropylene and polystyrene for high quality bio-oil production. Fuel Process. Technol., vol. 175, pp. 64–75, Jun. 2018, doi: 10.1016/j.fuproc.2018.02.019.
[27] R. Miandad et al. Influence of temperature and reaction time on the conversion of polystyrene waste to pyrolysis liquid oil. Waste Manag., vol. 58, pp. 250–259, Dec. 2016, doi: 10.1016/j.wasman.2016.09.023.
[28] P. A. Owusu, N. Banadda, A. Zziwa, J. Seay, and N. Kiggundu. Reverse engineering of plastic waste into useful fuel products. J. Anal. Appl. Pyrolysis, vol. 130, pp. 285–293, Mar. 2018, doi: 10.1016/j.jaap.2017.12.020.
[29] M. Rehan et al. Effect of zeolite catalysts on pyrolysis liquid oil. Int. Biodeterior. Biodegradation, vol. 119, pp. 162–175, Apr. 2017, doi: 10.1016/j.ibiod.2016.11.015.
[30] S. D. Anuar Sharuddin, F. Abnisa, W. M. A. Wan Daud, and M. K. Aroua. Energy recovery from pyrolysis of plastic waste: Study on non-recycled plastics (NRP) data as the real measure of plastic waste. Energy Convers. Manag., vol. 148, pp. 925–934, Sep. 2017.
[31] Ephraim, D. Pham Minh, D. Lebonnois, C. Peregrina, P. Sharrock, and A. Nzihou. Co-pyrolysis of wood and plastics: Influence of plastic type and content on product yield, gas composition and quality. Fuel, vol. 231, pp. 110–117, Nov. 2018, doi: 10.1016/j.fuel.2018.04.140.

[32] Muneer, M. Zeeshan, S. Qaisar, M. Razzaq, and H. Iftikhar. Influence of in-situ and *ex-situ* HZSM-5 catalyst on co-pyrolysis of corn stalk and polystyrene with a focus on liquid yield and quality. J. Clean. Prod., vol. 237, p. 117762, Nov. 2019, doi: 10.1016/j.jclepro.2019.117762.
[33] M. Razzaq, M. Zeeshan, S. Qaisar, H. Iftikhar, and B. Muneer. Investigating use of metal-modified HZSM-5 catalyst to upgrade liquid yield in co-pyrolysis of wheat straw and polystyrene. Fuel, vol. 257, p. 116119, Dec. 2019, doi: 10.1016/j.fuel.2019.116119.
[34] O. Sanahuja-Parejo et al. Drop-in biofuels from the co-pyrolysis of grape seeds and polystyrene. Chem. Eng. J., vol. 377, p. 120246, Dec. 2019, doi: 10.1016/j.cej.2018.10.183.
[35] M. Sogancioglu, E. Yel, and G. Ahmetli. Investigation of the Effect of Polystyrene (PS) Waste Washing Process and Pyrolysis Temperature on (PS) Pyrolysis Product Quality. Energy Procedia, vol. 118, pp. 189–194, Aug. 2017, doi: 10.1016/j.egypro.2017.07.029.
[36] M. Bartoli, L. Rosi, M. Frediani, A. Undri, and P. Frediani,. Depolymerization of polystyrene at reduced pressure through a microwave assisted pyrolysis. J. Anal. Appl. Pyrolysis, vol. 113, pp. 281–287, May 2015, doi: 10.1016/j.jaap.2015.01.026.
[37] P. Shadangi and K. Mohanty. Co-pyrolysis of Karanja and Niger seeds with waste polystyrene to produce liquid fuel. Fuel, vol. 153, pp. 492–498, Aug. 2015, doi: 10.1016/j.fuel.2015.03.017.
[38] Nisar et al. Fuel production from waste polystyrene via pyrolysis: Kinetics and products distribution. Waste Manag., vol. 88, pp. 236–247, Apr. 2019, doi: 10.1016/j.wasman.2019.03.035.
[39] K.-B. Park, Y.-S. Jeong, B. Guzelciftci, and J.-S. Kim. Two-stage pyrolysis of polystyrene: Pyrolysis oil as a source of fuels or benzene, toluene, ethylbenzene, and xylenes. Appl. Energy, vol. 259, p. 114240, Feb. 2020, doi: 10.1016/j.apenergy.2019.114240.
[40] R. Kumar Mishra and K. Mohanty. Co-pyrolysis of waste biomass and waste plastics (polystyrene and waste nitrile gloves) into renewable fuel and value-added chemicals. Carbon Resour. Convers., vol. 3, pp. 145–155, 2020, doi: 10.1016/j.crcon.2020.11.001.
[41] S. Kumar and R. K. Singh. Optimization of process parameters by response surface methodology (RSM) for catalytic pyrolysis of waste high-density polyethylene to liquid fuel. J. Environ. Chem. Eng., vol. 2, no. 1, pp. 115–122, Mar. 2014, doi: 10.1016/j.jece.2013.12.001.