**Proceedings of the ASME 2022
International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
IDETC/CIE2022
August 14-17, 2022, St. Louis, Missouri**

DETC2022-89199

MIXED PLASTIC WASTE CONVERSION TO VALUE-ADDED PRODUCTS: SUSTAINABILITY ASSESSMENT AND A CASE STUDY IN IDAHO

Galo Albor[1*], Amin Mirkouei[1,2], and Ethan Struhs[2]

[1] Department of Environmental Science, University of Idaho, Idaho Falls, ID 83402, USA
[2] Department of Mechanical Engineering, University of Idaho, Idaho Falls, ID 83402, USA

ABSTRACT

Value-added products from petroleum-based wastes (e.g., mixed plastics) have shown great potential to address sustainability challenges, such as global waste management and environmental pollution from petroleum-based products. However, recycling mixed plastic wastes (MPW) has been debated for producing renewable materials and value-added products, such as C10-C50 liquid hydrocarbon compounds. This study investigates the economic feasibility and sustainability benefits of producing MPW pyrolysis oil (p-oil), using a transportable refinery unit. The presented approach was evaluated by conducting a case study in southeast Idaho, USA. The techno-economic analysis calculates the total supply chain cost of the plastics pyrolysis conversion process. The life cycle assessment (LCA) evaluates the negative environmental impacts of MPW-to-products life cycle. LCA assesses the global warming potential for a 100-year time horizon. The p-oil production cost per metric ton is $228, while the total emission is 2,262 kg CO_2 per 100 metric tons of MPW. The results indicate that on-site operation can reduce plastic waste management and carbon footprint. Based on these results, converting MPW to liquid hydrocarbon products using the mobile pyrolysis conversion process can address the supply chain sustainability challenges and lead to sustainable production.

Keywords: Plastic Wastes; Mobile Refinery; Pyrolysis Oil; Value-added Products; Life Cycle Assessment; Techno-Economic Analysis; Sustainability.

NOMENCLATURE

Parameters

$A_{plastic}$ Amount of MPW (metric ton)
P_{yu} Annual plastic pyrolysis utilization (metric ton/yr)
$E_{c\text{-}cs}$ Annual capital cost of p-char storage ($/yr)
$E_{c\text{-}gr}$ Annual capital cost of grinding ($/yr)
$E_{c\text{-}py}$ Annual capital cost of plastic pyrolysis ($/yr)
$E_{c\text{-}tr}$ Annual capital cost of double-trailer truck ($/yr)
CS_u Annual p-char storage utilization (metric ton/yr)
$E_{v\text{-}cs}$ Annual variable cost of p-char storage ($/yr)
$E_{v\text{-}gr}$ Annual variable cost of grinding ($/yr)
$E_{v\text{-}os}$ Annual variable cost of p-oil storage ($/yr)
$E_{v\text{-}py}$ Annual variable cost of plastic pyrolysis ($/yr)
$E_{v\text{-}tr}$ Annual variable cost of double-trailer truck ($/yr)
E_1 Pretreatment cost ($/yr)
E_2 Conversion cost ($/yr)
E_3 Storage cost ($/yr)
E_4 Distribution cost ($/yr)
D Distance (miles)
GR_u Annual grinder utilization (metric ton/yr)
OS_u Annual bio-oil storage utilization (metric ton/yr)
$O_{p\text{-}oil}$ P-oil production GWP (kg CO_2 eq.)
O_{trans} P-oil transportation GWP (kg CO_2 eq.)
O_{up} Environmental impacts of upstream GWP (kg CO_2 eq.)
$Q_{p\text{-}oil}$ Quantity of produced p-oil (metric ton)
RCO_2 Emissions rate of CO_2 (kg CO_2 eq./kg CO_2)
RCH_4 Emissions rate of RCH_4 (kg CH_4 eq./kg CO_2)
RN_2O Emissions rate of N_2O (kg N_2O eq./kg CO_2)
TR_u Annual truck utilization (metric ton/yr)
$\beta_{p\text{-}oil}$ Oil production GHG emissions factor (kg CO_2 eq./ton)
$\beta_{p\text{-}oil, CO2}$ Oil production CO_2 emission factor (kg CO_2/ton)
$\beta_{p\text{-}oil, CH4}$ Oil production CH_4 emission factor (kgCH_4/ton)
$\beta_{p\text{-}oil, N2O}$ Oil production N_2O emission factor (kg N_2O/ton)
β_{trans} Oil transportation GHG emission factor (kg CO_2eq./ton-mile)
$\beta_{trans, CH4}$ Oil transportation CH_4 emission factor (kg CH_4/ton-mile)
$\beta_{trans, CO2}$ Oil transportation CO_2 emission factor (kg CO_2/ton-mile)

$\beta_{trans,N2O}$ Oil transportation N_2O emission factor (kg N_2O/ton-mile)
β_{up} Upstream GHG emissions factor (kg CO_2eq./ton)
$\beta_{up,CH4}$ Upstream process CH_4 emission factor (kg CH_4/ton)
$\beta_{up,CO2}$ Upstream process CO_2 emission factor (kg CO_2/ton)
$\beta_{up,N2O}$ Upstream process N_2O emission factor (kg N_2O/ton)

Decision Variables

$Char_{bct}$ P-char from conversion site b to storage site c during time period t (metric ton)
Oil_{bcdt} P-oil mass from conversion site b to storge site d during time period t (metric ton)
Oil_{cet} P-oil mass from storage site c to distribution center e during time period t (metric ton)
P_{abt} Plastic mass from collection center a to conversion b during time period t (metric ton)

1. INTRODUCTION

The increase in fossil fuel dependency and petroleum-based products (e.g., transportation fuels and plastics) consumption requires special attention to avoid depleting the natural resources due to the rapidly growing population and high global demand for improving the quality of life. Plastic is a well-diverse and highly versatile consumer product due to its low weight, high strength, and durability. These characteristics make plastics essential for many industries, such as packaging, transportation, and consumer electronics. As a result, the demand for plastic-based products is growing, where 99% of plastic production is petroleum-based, accounting for approximately 9% of global oil and gas consumption [1]. The increasing demand for plastic-based products results in direct or indirect waste generation, depending on their application range.

Plastic wastes pose a global hazardous threat to the environment due to their increment in the waste stream [2]. According to Environmental Protection Agency (EPA), plastic waste disposal is approximately 292 million tons of waste or 4.9 pounds per capita per day [3]. Prior studies report that over 3.4 billion tons of non-degradable plastic wastes will be generated annually by 2050 [4], and 32 million tons of plastic wastes enter the oceans per year [5]. Plastic waste pollution costs approximately \$2.5 trillion per year, including ocean damage, greenhouse gas (GHG) emissions, and land pollutants [6]. Recent studies indicate that plastic waste management is currently low, and it has been reported that only 9% of plastic waste has been recycled since its inception [3]. The continuous disposal of plastic waste predicts severe environmental and health hazards, such as bacterial contamination, increased methane, and disease risk [4]. The existing plastic recycling operations are not cost-competitive due to the low quality of intermediate and final products, which reduces the sustainability benefits of a circular economy. Plastic wastes can be reused to generate new brand plastics and value-added liquid hydrocarbon products that stand as a better strategy solution to tackle the environmental problems and compensate for petroleum-based products. The US Department of Energy (DOE) has recently invested \$25 million in plastic waste recycling to combat plastic pollution across food-energy-water systems and achieve a circular economy [7].

1.2. Background

Improving the existing technologies (e.g., thermochemical and biochemical processes) can provide opportunities to recycle petroleum-based wastes (e.g., plastic-based products) and overcome the global environmental crisis due to the high demand and consumption over the past decade. **Figure 1** provides common representations of different plastic types, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polystyrene (PP), and polystyrene (PS).

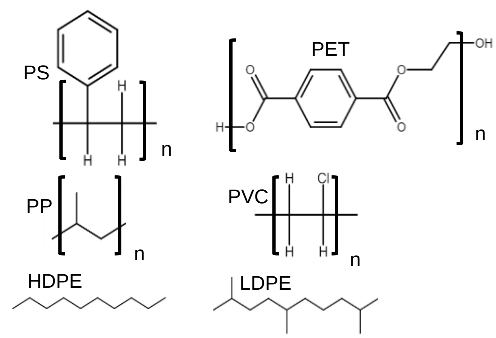


Figure 1. Common plastic types and their chemical structures

Pyrolysis is one of the commercialized thermochemical processes that can convert mixed plastics wastes to pyrolysis oil (p-oil) and pyrolysis char (p-char) with high process yield and product quality. Pyrolysis can break down long-chain hydrocarbons into small polymer molecules (shorter-chain hydrocarbon) at high temperatures (400-600°C) [8–10]. P-oil from plastics pyrolysis can be upgraded to different liquid hydrocarbons with many applications due to various boiling points, including transportation fuels (e.g., kerosene and diesel) and motor oil [11,12]. Prior studies reported that catalytic pyrolysis has a high process yield (up to 75%) and could be a viable solution for plastic recycling and overcome sustainability challenges [13]. Despite the advantages, catalytic pyrolysis has several disadvantages, such as high catalyst cost and low refinery lifetime. The American Chemistry Council (2011) reported that a commercial facility could process between 7,500 and 10,000 tons per year with a capital cost ranging from \$4 million to \$11.5 million [14]. Transparency market research (2021) reported that the plastic waste recovery market is expected to reach \$100 million by 2027 [15].

Plastic wastes recycling strategies. Various studies (as presented in Table 1) have conducted feasibility analyses for plastic waste recycling using different conversion technologies (e.g., pyrolysis and liquefaction) and provided the gateway to reduce the degradation of diverse ecosystems [16]. The pyrolysis process showed a promising recovery approach from mixed landfill plastic wastes [17,18]. Recent studies reported that the main parameters for process yield are the process temperature

(162-340°C), pressure (20-100 psi), and operation time (0.5-2.5 hours) for producing C10-C50 hydrocarbon products [19]. Banue et al. (2020) reported up to 85% process yield for plastic conversion via pyrolysis with temperatures between 450°C and 650°C and pressure from 116 to 623 psi while maximizing output and reducing the production cost [20]. A comprehensive overview for mitigating the plastic waste crisis and producing value-added products has been given by recent studies, such as Cabanes and Fullana (2021), EPA (2020a), Meys et al. (2020).

Environmental impacts assessment. Plastic wastes recycling provides numerous environmental benefits, such as mitigating global warming potential (GWP), ozone depletion, human toxicity, terrestrial acidification, and ecotoxicity [22]. Life cycle assessment (LCA) is a standard method for evaluating the environmental impacts of plastic waste recycling and p-oil production, considering different system boundaries and functional units. Several studies have applied the LCA method, and their results show the environmental benefits of plastic waste recycling in various countries, such as Brazil, Iran, and the United States [22–24]. Benavides et al. (2017) conducted an LCA study on plastic wastes conversion to value-added products. The study concluded that by transforming waste into products can reduce up to 14% of GHG emissions compared to original petroleum-based products by utilizing 58% less water and 96% lower consumption fossil fuels [24]. In addition, several studies reported that processing plastic waste is less harmful in comparison to open dumping and sanitary landfilling [25].

Techno-economic assessment (TEA). A recent study reported that current MPW-based oil on 2018 market value at $37 million, and it expects to grow approximately 10% per year and reach $100 million by 2027 [26]. In addition, other studies reported that plastic waste has a value of up to $1,200 per metric ton (**Table 1**). However, there is little research exclusively on the economic assessment of non-recyclable plastic wastes, and most of the conducted studies have several assumptions (American Chemistry Council, 2011). Gracida-Alvarez et al. (2019) reported that plastic waste conversion to energy recovery is a promising application on an industrial scale [27]. Several studies also noted that the conversion of plastic wastes to various products and byproducts could minimize the total costs and maximize profitability [28,29].

1.3. Goal and Scope

This work combined LCA and TEA multi-criteria decision making to (a) explore the sustainability benefits of liquid hydrocarbons production from MPW and (b) explore the commercial feasibility of liquid hydrocarbons production, using an actual case study in southeast Idaho, USA, for validating the proposed methods and models. Furthermore, the economic and environmental analysis aims to determine the viability of p-oil and p-char production under the possible use of transportable refinery units to convert MPW to value-added products near the collection sites and reduce the environmental footprint of plastic wastes management. The assessment covers the total supply chain cost for p-oil and p-char production and distribution. In addition, the LCA evaluates the GWP_{100} of plastic waste-based oil production processes and distribution networks, using the LCA method, including four phases (i.e., goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation). Finally, a case study in southeast Idaho investigates the sustainability benefits of the proposed conversion process in regions with a high density of plastic wastes. In addition, it demonstrates the applicability of the method in recycling petroleum-based wastes.

Table 1. Comparable economic and environmental studies on mixed plastic waste conversion.

Study	Environmental	Economic	Pyrolysis	Resource	Method
[30]	×	✓	✓	Municipal Solid Waste	TEA & Experimental
[17]	✓	×	×	Municipal Solid Waste	LCA
[31]	×	×	✓	Plastic waste	Experimental
[24]	✓	×	✓	Plastic waste	LCA
[32]	×	✓	✓	Plastic	TEA & HYSY
[27]	×	✓	✓	High-density Polyethylene	TEA
[33]	×	✓	✓	Mixed Plastic	TEA
[34]	×	✓	✓	Mixed Polyolfefins	TEA
[28]	×	✓	✓	Landfill waste	TEA
[35]	×	✓	×	Polyurethane rubber	TEA
[36]	✓	✓	✓	Polypropylene	TEA &LCA
[13]	✓	×	✓	Plastic packaging waste	LCA
[29]	×	✓	✓	Municipal solid waste	TEA
[25]	✓	✓	✓	Municipal solid waste	TEA & LCA
This Study	✓	✓	✓	Mixed Plastics	TEA & LCA

2. MATERIALS AND METHODS

The pyrolysis process for the MPW to value-added products is divided into collection/transportation, pretreatment, conversion, storage, and distribution. The plastic wastes are collected and transported to the mobile refinery unit close to the collection center. The pretreatment process for size reduction uses a VeconPlan Vaz 1600-M-XL grinder. The transportable pyrolysis refinery was used to perform MPW pyrolysis experiments to determine the MPW characteristics yield and primary products (i.e., p-oil, p-char, and p-gas). The pyrolysis process involves the thermochemical decomposition of plastic wastes at a higher temperature (300–600°C) in the absence of oxygen. Aspen HYSYS process simulator was used to model the MPW pyrolysis reactor with a capacity of approximately 50 metric tons per day while using a continuously stirred-tank reactor (CSTR) due to their ability to model kinetic reactions (**Figure 2**). The reactor was purged with nitrogen at a 10-20 L/min flow rate to control the reactor residence time and promote feedstock decomposition. The plastic waste enters the reactor at room temperature, and the pyrolysis unit operates under 0-55psi pressure and 400-600°C temperature with a residence time of 20-60 minutes. The converted condensable vapor goes through a

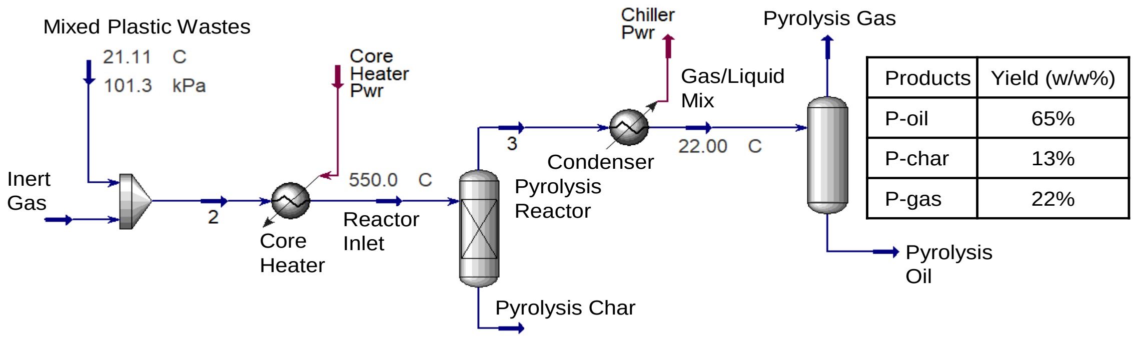


Figure 2. Schematic Aspen HYSYS simulation of p-oil and p-char production

condenser unit to separate the primary pyrolysis byproducts. Finally, the obtained p-oil and p-char are transported to an upgrading facility or p-char distribution center, respectively. The moisture content of MPW is one of the critical parameters affecting process yield and products quality [37,38].

This study evaluates the market opportunity and sustainability benefits of liquid hydrocarbons produced from MPW using a transportable pyrolysis conversion pathway. The developed methodology in this study includes LCA for evaluating environmental impacts and mathematical TEA modeling for assessing the total cost of p-oil production from MPW (**Figure 3**).

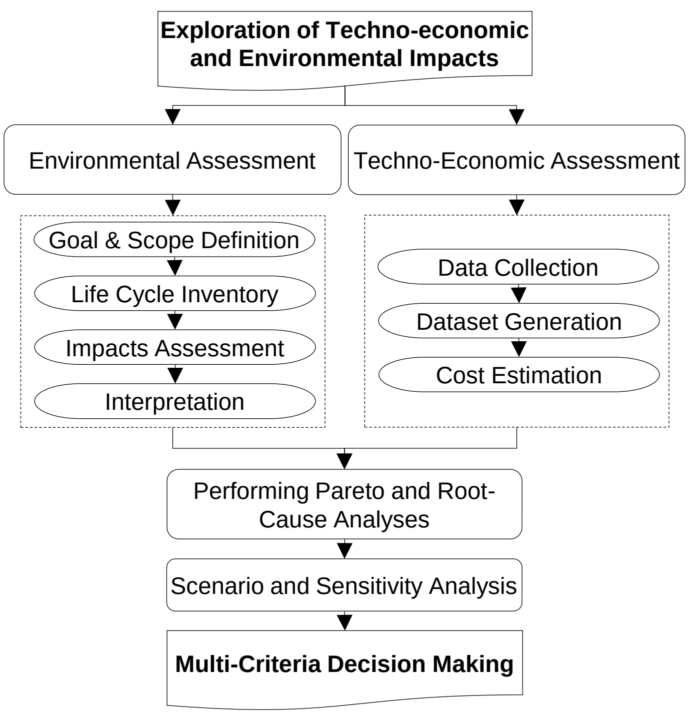


Figure 3. Multi-criteria decision-making framework for sustainability assessments

2.1. Environmental Impact Assessment

The LCA study describes in detail the approach used for performing the environmental impacts of converting MPW to value-added products utilizing OpenLCA databases and data from previous studies to assess.

Goal and scope definition. The goal of the LCA is to measure the life cycle impacts of pyrolysis of MPW to value-added products. Furthermore, this study investigates GHG emissions, including CO_2, CH_4, and N_20, and the emission factor is in kg CO_2 equivalent with the emissions being 1 kg CO_2 eq./kg CO_2, 28 kg CO_2 eq./kg CH_4 and 265 kg CO_2 eq./kg N_2O. Methods and data were obtained from the Intergovernmental Panel on Climate Change for a 100-year time horizon [39]. The scope of this work involves various segments that can be classified into three sectors: (a) upstream, including plastic wastes collection and on-site pretreatment, (b) midstream, including the conversion of plastic into products (e.g., p-oil, p-char, and p-gas), and (c) downstream, including distribution of p-oil for future upgrading and p-char for end-use. In addition, the LCA study has considered a grave-to-gate system, including recycling MPW and bringing them back to life as input materials for any applications. The utilized units in this study are a metric ton of MPW and a gallon of p-oil.

Life cycle inventory analysis. The MPW conversion and distribution processes were analyzed using quantitative data from the European Reference Life Cycle Database and OpenLCA databases for the input and output parameters [40]. The necessary equipment operated during the upstream collection of MPW included a dump lorry and skid-steer. Input into the centralized collection stage is petroleum-based MPW, transportation fuels (e.g., diesel), and heavy equipment lubricants. Outputs comprise CO_2 emitted from MPW and equipment operations emissions. Therefore, the GHG emissions factor for the upstream consists of collecting and hauling MPW and feeding MPW into the grinder for size reduction. Upstream pretreatment inputs are disposal MPW diesel, and the outputs are pretreated MPW and GHG emissions. GWP is impacted by plastic dust release and the quality of the feedstock. The midstream process starts by processing the pretreated MPW through a plastic pyrolysis unit, using nitrogen as an inert gas and heat elements source powered by electricity. Plastic pyrolysis inputs are pretreated feedstocks, nitrogen for feeding, electricity for thermochemical, and water for condensing/cooling purposes. The outputs conversion includes p-oil and p-char as value-added products and pyrolysis gas as emissions. The breakdown of plastics pyrolysis by the percentage of products weight are 65% p-oil, 13% p-gas, and 22% p-char, respectively [41]. Non-biogenic GHG and ash are additional emissions from the conversion process and combustion of p-gas. During the downstream process, produced p-oils and p-chars will be transported by tanker trucks or double-trailer trucks (consuming diesel fuel) to upgrading refineries or distribution centers, respectively. The emissions produced by the fuel consumption depend on the distance from the conversion refinery to the upgrading or distribution sites. The p-char produced can also be applied in the pretreatment or pyrolysis processes as the heat source for drying MPW or thermochemical conversion.

Life cycle impact assessment (LCIA). LCIA was accomplished by utilizing the CML-IA baseline method, developed by Chalmers University of Technology (version 2.0.5), and production systems using OpenLCA (an open-source LCA software), aiming at p-oil production from MPW. The total GHG emissions are calculated using **Equations 1-6** system boundaries method of the p-oil production and the inputs and outputs to perform LCA.

$$\beta_{up} = R_{CO2} \times \beta_{up,\,CO2} + R_{CH4} \times \beta_{up,\,CH4} + R_{N2O} \times \beta_{up,\,N20} \quad (1)$$

$$O_{up} = A_{Plastic} \times \beta_{up} \quad (2)$$

$$\beta_{p\text{-}oil} = R_{CO2} \times \beta_{p\text{-}oil,\,CO2} + R_{CH4} \times \beta_{p\text{-}oil,\,CH4} + R_{N2O} \times \beta_{up,\,N20} \quad (3)$$

$$O_{p\text{-}oil} = Q_{p\text{-}oil} \times \beta_{p\text{-}oil} \quad (4)$$

$$\beta_{trans} = R_{CO2} \times \beta_{trans,\,CO2} + R_{CH4} \times \beta_{trans,\,CH4} + R_{N2O} \times \beta_{trans,\,N20} \quad (5)$$

$$O_{trans} = Q_{p\text{-}oil} \times \beta_{trans} \times D \quad (6)$$

Interpretation. The results from the conducted LCA study show the quantitative analysis of the environmental impacts involved in recycling 100 metric tons per day of MPW. This study uses the GWP_{100} time horizon to analyze GHG emissions and human toxicity. Considering this information is crucial to understanding the environmental impacts of the defined system boundary (input and outputs parameters) and will be a key for enhancing sustainability benefits. The emissions produced by the value-added products (e.g., p-oil and p-char) are categorized as non-renewable since 99% of plastic production is petroleum-based. The major contributor to GWP_{100} is CO_2 emitted from MPW management, reducing when MPWs are reused to other products, such as HDPE, p-oil, or p-char. Additional major GHG contributors are pretreatment and transportation operations.

2.2. Techno-economic Analysis

The formulated mathematical model (Eq. 7) calculates the total cost of p-oil production from MPW using mobile pyrolysis refinery units. The TEA model considers capital and operational costs of pretreatment (Eq. 8), conversion (Eq. 9), p-oil and p-char storage (Eq. 10), and distribution (Eq. 11) steps. This study does not consider the collection cost of MPW since most cities have programs for plastic waste management [42]. The primary objective is to estimate the expenses of converting MPW to p-oil over a 1-year time horizon. Details about the parameters, variables, and indices are provided in the Nomenclature section.

$$Total\ Cost = E_1 + E_2 + E_3 + E_4 \quad (7)$$

$$E_1 = \sum_a \sum_b \sum_t (E_{C-gr} + E_{V-gr}) \times \frac{P_{abt}}{GR_u} \quad (8)$$

$$E_2 = \sum_a \sum_b \sum_t (E_{C-py} + E_{V-py}) \times \frac{P_{abt}}{PY_u} \quad (9)$$

$$E_3 = \sum_b \sum_c \sum_t (E_{C-cs} + E_{V-cs}) \times \frac{Char_{bct}}{CS_u} + \sum_b \sum_d \sum_t (E_{C-os} + E_{V-os}) \times \frac{Oil_{bdt}}{OS_u} \quad (10)$$

$$E_4 = \sum_c \sum_e \sum_t (E_{C-tr} + E_{V-tr}) \times \frac{Oil_{cet}}{TR_u} \quad (11)$$

3. CASE STUDY

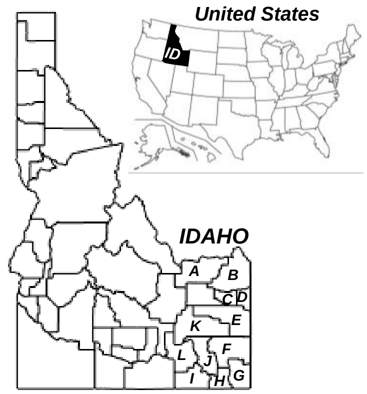
Idaho is the 2nd fastest-growing state in the USA, with a total population increase of 2.1% from 2019 [43]. Idaho is attractive to people from across the country for its diverse amenities and lower cost of living. Some amenities include living in a less dense city providing reasonable commutes, diversity of outdoor activities, and prosperity. This study explored a case study in southeast Idaho, and **Table 2** provides the estimates of MPW disposal in southeast counties, such as Madison, Bonneville, Bannock, and Bingham. Southeast Idaho process approximately 1,768,810 lbs./day (802 metric tons) or 645,6150 lbs/yr (292,846 metric tons per year) of MPW with an estimated population of 353,762, according to the US Census Bureau [44]. The total number of collection sites is 12, assuming the appropriate local authorities will distribute the MPW to the centralized recycling facility. This study utilizes various equipment for pretreatment (grinding), refinery (pyrolysis), and transportation (trucks).

Additionally, the following assumptions are made, using the available data and estimates reported in published studies:

- The refinery capacity for a single mobile pyrolysis unit is 50 metric tons of ground MPW.
- The time horizon is one year.
- All dollar amounts used in this study are US dollars (USD).
- MPW collection cost is omitted due to existing programs by local authorities in regions with a high density of MPW [42].
- The annual schedule refinery process is 328 days and 12 hours per day [45,46].
- The average MPW available is 322,162 metric tons in the southeast Idaho region [44].
- Loader and grinder utilization rates are 60,000 and 37,500 per year, respectively [47].
- MPW pretreatment rate is assumed 100%.
- Pyrolysis conversion process yields for p-oil, p-char, and p-gas are 65%, 13%, and 22%, respectively [29].
- The round-trip distance from the mobile refinery facility to the upgrading facility is 420 miles (676 km) (ArcGIS 2019).
- The round-trip distance from the mobile refinery facility to the p-char storage facility is assumed 100 miles (160 km) (ArcGIS 2019).

Table 2. Southeast Idaho MPW Collection Area (Bureau, 2019)

Geographic Area	2019 Population	MPW per Day	MPW per Year
A. Clark	845	4,225	1,542,125
B. Fremont	13,099	65,495	23,905,675
C. Madison	39,907	199,535	72,830,275
D. Teton	12,142	60,710	22,159,150
E. Bonneville	119,062	595,310	217,288,150
F. Caribou	7,155	35,775	13,057,875
G. Bear Lake	845	4,225	1,542,125
H. Franklin	13,876	69,380	25,323,700
I. Oneida	4,531	22,655	8,269,075
J. Bannock	87,808	439,040	160,249,600
K. Bingham	46,811	234,055	85,430,075
L. Power	7,681	38,405	14,017,825
Total	353,762	1,768,810	645,615,650



P using the available data and estimates reported in published studies:

- The refinery capacity for a single mobile pyrolysis unit is 50 metric tons of ground MPW.
- The time horizon is one year.
- All dollar amounts used in this study are US dollars (USD).
- MPW collection cost is omitted due to existing programs by local authorities in regions with a high density of MPW [42].
- The annual schedule refinery process is 328 days and 12 hours per day [45,48].
- The average MPW available is 322,162 metric tons in the southeast Idaho region [44].
- Loader and grinder utilization rates are 60,000 and 37,500 per year, respectively [47].
- MPW pretreatment rate is assumed 100%.
- Pyrolysis conversion process yields for p-oil, p-char, and p-gas are 65%, 13%, and 22%, respectively [29].
- The round-trip distance from the mobile refinery facility to the upgrading facility is 420 miles (676 km) (ArcGIS 2019).
- The round-trip distance from the mobile refinery facility to the p-char storage facility is assumed 100 miles (160 km) (ArcGIS 2019).-oil tanker is considered part of the refinery unit, and associated costs are included in the refinery operation expenditures [49].
- This study does not consider the sustainability benefits of p-char in p-oil production [50].

4. Results

The results indicated that the proposed approach could recycle 32,800 metric tons of MPW and produce 21,320 metric tons of p-oil (approximately 608,899 gallons of hydrocarbon fuel) over a one-year time horizon. The collection and sorting costs are omitted, assuming that the local authorities in regions with a high density of municipal solid wastes have a program to manage and recycle the wastes [42]. The total cost and unit p-oil cost, employing two transportable refineries (Main Case Study) with 100 metric tons per day capacity, is estimated at $4,860,637 per year and $228 per metric ton ($0.88 per gallon of p-oil), respectively. However, the pretreatment cost outweighs the cost of MPW disposal management, as well as negative environmental impacts. For example, if a metric ton of disposable MPW costs approximately $33,000 per metric ton, the total benefit lost from the ecosystems for 32,800 metric tons would be roughly $1,082,400,000 [6]. **Table 3** presents the capital and operational costs of each process. Approximately 78% of the total cost is due to operating costs. The pyrolysis and grinding processes are the two major operational cost-drivers due to high energy consumption, particularly 43 gallons per hour in eight-hour shift grinding operations.

Table 3. Capital and operational costs, and annual utilization rate for each process

Step to step	Process	Capital cost ($/yr)	Operational cost ($/yr)	Utilization rate (metric ton/yr)
a to b	Grinding	214,800	751,900	1,137,500
a to b	Pyrolysis	485,298	1,256,503	16,400
b to c	P-char storage	80,798	167,034	4,264
b to d	P-oil storage	182,653	383,571	21,320
c to e	Transportation	87,588	285,846	50,000
Total	-	1,239,073	2,844,854	1,229,484

4.1 Environmental impact assessment results

The conducted LCA study explores the proposed approach in this study as a solution to overcome the current MPW crisis that the world is enduring. The environmental impacts of recycling 100 metric tons of MPW per day results in approximately 2,262 kg of CO_2 eq. for producing a metric ton of p-oil and p-char. **Table 4** presents the results of the MPW pyrolysis process using the data from OpenLCA 1.10.3 and prior published studies and defined assumptions for the proposed southeast Idaho case study.

Table 4. Total emissions for one metric ton of p-oil and p-char production from plastic pyrolysis

Process	CO_2	N_2O (10^{-5})	CH_4 (10^{-4})	GWP
Collection/transportation	8.06	6.31	3.23	17.61
Grinding	922.42	722.05	370.05	2,014.52
Conversion	81.95	64.15	32.88	178.98
P-oil transportation	22.14	17.33	8.88	48.36
P-char transportation	1.05	0.82	0.42	2.29
Total	1,035.63	810.67	415.47	2,261.76

The results show that plastic recycling using pyrolysis is a sustainable approach in regions with a high density of MPW. The analysis expresses the effectiveness of reducing environmental impacts during the plastics-to-oil recycling process by eliminating MPW disposal to landfills. The majority of GWP emissions are saved from discharging into the environment and preventing health damage to ecosystems. The data from the LCA analysis was used for conducting Pareto analysis, which is essential to compare the results and gain a sound understanding of each step. Pareto analysis is utilized to analyze each process overall GHG emissions (kg CO_2 eq.) across pyrolysis pathways and compare the GWP environmental impacts of end-use of MPW in its life cycle (**Figure 4**).

The Pareto analysis, known as the 80/20 law, was used to identify 20% of causes (processes) that are responsible for 80% of problems (emissions). Even in cases where the data does not strictly follow the rule, the analysis can be informative. Inputs and outputs are unequally distributed, which causes some inputs to contribute more than others in the environment and economic outcomes. The pretreatment step contributes to most of the GHG emissions and GWP. Reducing the pretreatment emissions could be achieved by employing new technologies and renewable fuels, such as biodiesel.

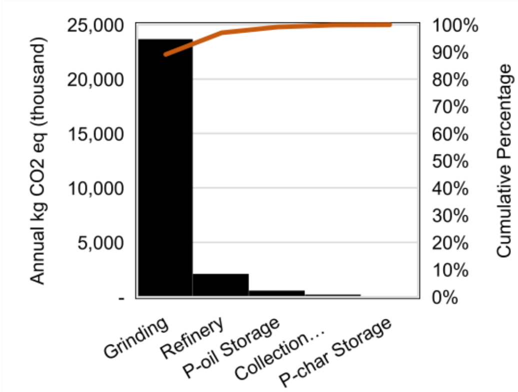


Figure 4. Pareto analysis of the impact of each process on the environment

5. Sensitivity Analysis and Discussion

MPW-based hydrocarbon products can complement conventional petroleum-based fuels for internal combustion engines [31]. Several parameters and variables can affect TEA and LCA results of p-oil production. Sensitivity analysis is conducted herein to explore the effects of significant parameters on economic and environmental performance. The results show that grinding, conversion, and transportation are three key factors. Key benchmarks assessed in the sensitivity analysis include the number of refinery units utilized and their total cost. Four scenarios are analyzed and compared with the main case study that provides further insights for enhancing sustainability benefits. **Figure 5** presents a fishbone diagram to understand better the cause and effect of techno-economic and environmental variables throughout the MPW-based oil life cycle. Scrutinizing the supply chains (e.g., grinding and transportation) illustrates that the emissions from fuel combustion had significant impacts on total GHG emissions. In addition, p-gas from the MPW conversion process comprises propane, ethylene, ethane, methane, carbon dioxide, carbon monoxide, and butane. Additionally, root-cause analysis demonstrates the facets of economic, environmental, and safety challenges, as well as the potential causes throughout the plastics-to-oil life cycle.

Impact of transportable pyrolysis refinery cost. The main case study is the transportable refinery unit major cost-driver of p-oil production. Therefore, examining the effects of refinery cost is important to assess the profitable viability of MPW-based oil production by performing two additional case studies: Case Study 1, the refinery cost is reduced by 50%, and Case Study 2, the refinery cost is increased by 50% compared to the Main Case Study. **Table 5** reports the total cost results for each case study. The results indicated that changes in refinery cost significantly affect the total cost. The overall annual cost decreased in Case Study 1 by about $1,568,845 (-36%) and Case Study 2, the annual cost increased by $2,597,622 (+ 59%).

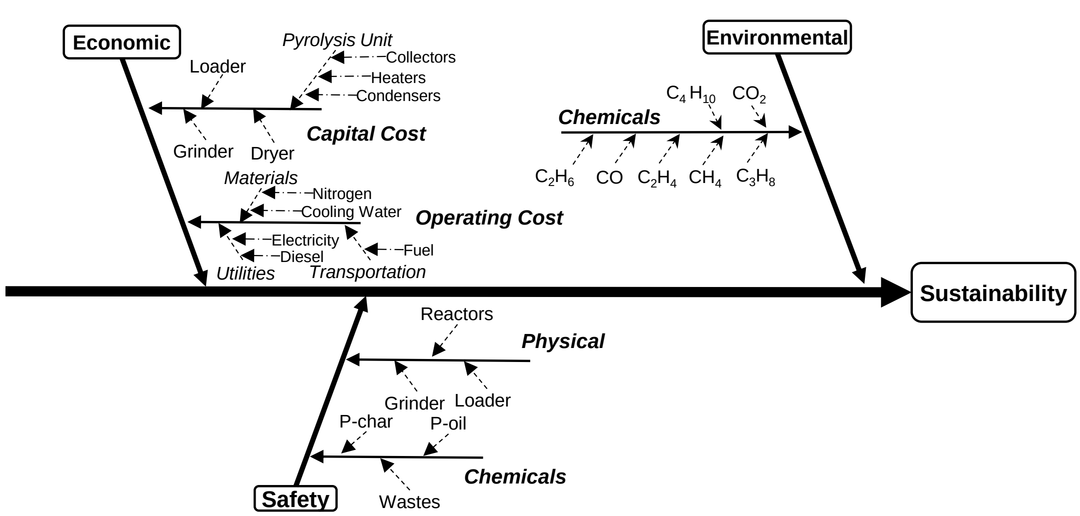


Figure 5. Fishbone diagram for sustainability root-cause analysis

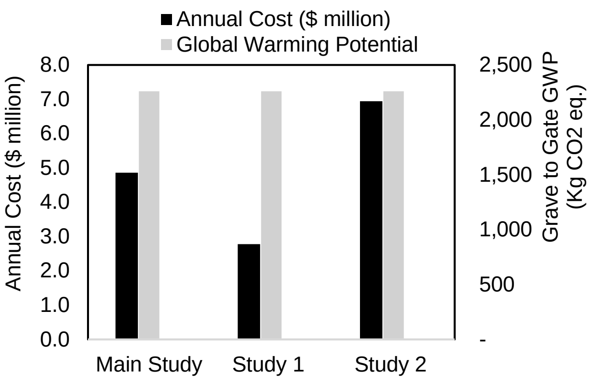


Figure 6. Effects of mobile refinery unit on economic and environmental aspects

Table 5. Effects of mobile refinery unit on the overall annual cost

Case Studies	Annual Overall Cost ($)	Annual Refinery Cost ($/yr)		
		Capital Cost	Operational Cost	Labor Cost
Main Case Study	4,346,249	673,234	1,256,503	432,410
Study 1(-50% cost)	2,777,404	336,617	628,251.5	216,205
Study 2(+50% cost)	6,943,871	1,009,851	1,884,755	648,615

Two refineries were utilized in all three case studies with a capacity of 100 metric tons per day for recycling MPW. As a result, the amount of recycled MPW remains constant, and GWP (kg CO_2 eq.) emissions stay the same as Main Case Study, Case Study 1, and Case Study 2, respectively (**Figure 6**).

Impact of the accessible amount of MPW. The available amount of MPW is a primary commercialization barrier for p-oil production. Since the availability can vary depending on local policy conditions, this study investigated the effects on the commercial feasibility of p-oil. The total amount of MPW disposal is 322,162 metric tons per day and was calculated based on the population in southeast Idaho for the main case study. The total amount of processed MPW is 32,800 metric tons per year. The total disposal amount of MPW obtainable is vital because it is the main parameter and changing the amount of available MPW affects the total annual cost. Therefore, it is essential to use multiple refineries to recycle annual MPW disposal. The implementation of refineries could affect the total yearly cost of the conversion and distribution supply chain and the total annual GWP emissions. The Main Case Study considers two refineries. In Case Study 3, the available amount of MPW decreased by 50%, and in Case Study 4, the available MPW increased by 50%. **Table 6** provides the estimated cost and environmental impacts for each case study.

Table 6. Effects of the available amount of MPW on the associated costs and environmental impacts

Studies	Amount of Plastic (metric ton)	P-oil Production ($/gallon)	GWP (kg CO_2 eq./metric ton)
Main Case Study	32,800	0.88	2,261.76
Study 3(-50% MPW)	16,400	1.18	1,759.57
Study 4(+50% MPW)	49,200	0.83	3,161.08

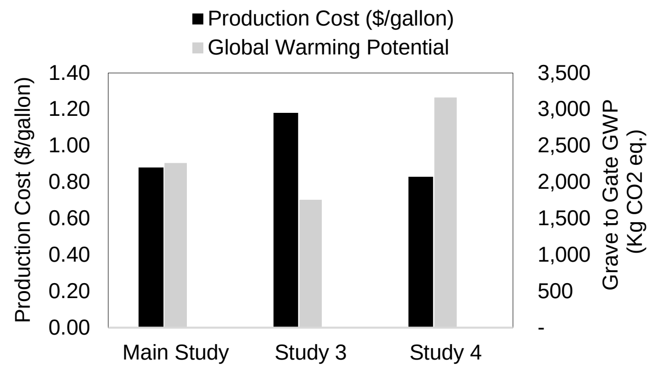


Figure 7. Effects of the available amount of MPW on economic and environmental aspects

In comparison with Main Case Study, the results show that p-oil production cost per metric ton (or $/gallon) increased by approximately 34% ($0.30) in Case Study 3, while p-oil production cost decreased by about 6% ($0.05) in Case Study 4. Also, GWP_{100} decreased by approximately 502 CO_2 kg eq. per metric ton in Case Study 3 (22%), while GWP_{100} increased by around 899 CO_2 kg eq. per metric ton in Case Study 4 (28%). The effects of MPW availability on the different case studies are shown in **Figure 7.**

In this study, the resulting unit price for p-oil production from disposal MPW indicates a reasonable comparison to the prices reported in recently published studies with similar operation capacity (**Table 7**). Recycling MPW has the potential to address national priorities (e.g., plastic wastes management and recycling) and sustainability challenges (e.g., environmental pollution from single-use plastics). Using MPW for p-oil and p-char production can increase investment in recycling processes, create jobs in the US, and reduce MPW discharge to the environment [50,51].

While technological advance is evolving, it is essential to produce secondary products. Byproducts from plastic pyrolysis (e.g., p-char) can be applied for producing alternative, environmental-friendly products, such as asphalt, concrete, and building bricks. For example, MPW-based asphalt for road construction has shown superior performance compared to conventional tar roads. In addition, p-char from MPW could be integrated into concrete and building bricks, providing different plastic properties, which benefits the construction structures [28]. The creation of byproducts helps facilitate the monetization of environmental benefits and avoids ecological costs, such as soil and air degradation.

Table 7. Estimated p-oil production cost comparison in recent studies

Technology	Capacity (metric ton/day)	p-oil production ($/gal)	Study
Pyrolysis	100	0.16	[32]
Pyrolysis	500	0.09	[27]
Pyrolysis	40	0.65	[33]
Pyrolysis	110	1.03	[29]
Pyrolysis	100	0.60	[52]
This study	100	0.88	

6. Conclusion

Pyrolysis technology is a pathway for p-oil and p-char production from MPW and an alternative solution to address the global plastic waste crisis. Furthermore, MPW-based p-oil production can promote carbon management systems and GHG emissions mitigation efforts. This study investigates the techno-economic and environmental aspects of the plastics-to-oil life cycle, using multi-criteria decision making, including LCA and TEA methods. The novelty of this study lies in exploring the sustainability benefits of MPW to value-added products (e.g., liquid hydrocarbons) and investigating the commercial feasibility of the proposed approach, using an actual case study in southeast Idaho, USA. In addition, this study investigates the feasible use of mobile refineries to convert MPW to value-added products near the collection sites and explores the environmental footprint of MPW management. The techno-economic study investigates the total cost of p-oil production and distribution (i.e., grinding, conversion, storage, and transportation). The environmental assessment evaluates GWP (GHG emissions, CO_2 kg eq.) for a 100-year time horizon grave-to-gate system boundary, including recycling MPW and bringing them back to life as input materials for any applications. The functional unit is a metric ton of MPW and a gallon of p-oil. The case study in southeast Idaho demonstrates the sustainability benefits of the proposed methods in regions with a high density of plastic wastes. Furthermore, it demonstrates the applicability of the method in recycling petroleum-based wastes. The total cost of p-oil production is approximately $228 per metric ton ($0.88 per gallon of p-oil), and the total emission is about 2,262 kg CO_2 per 100 metric tons of MPW processed.

The overall results of this study indicated the transportable refinery could manage the plastic wastes in high dense regions to produce value-added products (e.g., liquid hydrocarbon and pyrolysis char) and reduce environmental impacts (GHG emissions) of conventional MPW handling. It is concluded that recycling operations near the collection sites can reduce the unit price and carbon footprint of MPW management, address upstream and midstream sustainability challenges, and stimulate the plastic pyrolysis industry. Potential paths for future research and development include: (a) the exploration of social and biodiversity benefits associated with land, water, and habitat enhancement; (b) exploration of a mixed-mode conversion process and mixed-pathway transportation, and multiple-year operation to assess the broader sustainability benefits; (c) exploration of upstream, midstream, and downstream segments to identify commercialization and policy barriers.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the College of Engineering and Renewable and Sustainable Manufacturing Laboratory (RSML) research group at University of Idaho for providing resources and materials for this project.

REFERENCES

[1] Nielsen, T. D., Hasselbalch, J., Holmberg, K., and Stripple, J., 2020, "Politics and the Plastic Crisis: A Review throughout the Plastic Life Cycle," WIREs Energy Environ., **9**(1).

[2] Idumah, C. I., and Nwuzor, I. C., 2019, "Novel Trends in Plastic Waste Management - University of Idaho," SN Appl. Sci.

[3] EPA, O., 2017, "National Overview: Facts and Figures on Materials, Wastes and Recycling," US EPA [Online]. Available: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials. [Accessed: 22-Mar-2021].

[4] EPA, 2020, *United States Federal Strategy for Addressing the Global Issue of Marine Litter*, 160K20001.

[5] EPA, 2020, "Rethinking Plastic Packaging - How Can Innovation Help Solve the Plastic Waste Crisis?," EPA [Online]. Available: https://www.epa.gov/trash-free-waters/rethinking-plastic-packaging-how-can-innovation-help-solve-plastic-waste-crisis. [Accessed: 03-Feb-2021].

[6] Soloviy, V., 2019, "Marine Plastic Waste Costs Us Trillions in Losses," Sustainability Times.

[7] DOE, 2021, "Department of Energy to Invest $25 Million in Polymer Upcycling, Plastic Waste Reuse Research," Energy.gov [Online]. Available: https://www.energy.gov/science/articles/department-energy-invest-25-million-polymer-upcycling-plastic-waste-reuse-research. [Accessed: 12-Aug-2021].

[8] Mirkouei, A., Mirzaie, P., Haapala, K. R., Sessions, J., and Murthy, G. S., 2016, "Reducing the Cost and Environmental Impact of Integrated Fixed and Mobile Bio-Oil Refinery Supply Chains," Journal of cleaner production, **113**, pp. 495–507.

[9] Mirkouei, A., and Kardel, K., 2017, "Enhance Sustainability Benefits Through Scaling-up Bioenergy Production from Terrestrial and Algae Feedstocks," *Proceedings of the 2017 ASME IDETC/CIE: 22nd Design for Manufacturing and the Life Cycle Conference*.

[10] Mirkouei, A., and Haapala, K. R., 2015, "A Network Model to Optimize Upstream and Midstream Biomass-to-Bioenergy Supply Chain Costs," *ASME 2015 International Manufacturing Science and Engineering Conference (MSEC), MSEC2015-9355*.

[11] Bilal, M., and Iqbal, H. M. N., 2019, "Sustainable Bioconversion of Food Waste into High-Value Products by Immobilized Enzymes to Meet Bio-Economy Challenges and Opportunities - A Review," Food Res. Int., **123**, pp. 226–240.

[12] Zhang, L., Bao, Z., Xia, S., lu, Q., and Walters B., K. B., 2018, "Catalytic Pyrolysis of Biomass and Polymer Wastes - University of Idaho," Catalysts.

[13] Meys, R., Frick, F., Westhues, S., Sternberg, A., Klankermayer, J., and Bardow, A., 2020, "Towards a Circular Economy for Plastic Packaging Wastes – the Environmental Potential of Chemical Recycling," Resources, Conservation and Recycling, **162**, p. 105010.

[14] American Chemistry Council, 2011, *Conversion Techonology: A Complement to Plastic Recyling*.

[15] Press Release Newswire, T. M., and Rohit, B., 2021, "Recycled Plastic and Plastic Waste to Oil Market to Expand with Revolutionary Changes in the Energy Industry: TMR" [Online]. Available: https://www.prnewswire.com/news-releases/recycled-plastic-and-plastic-waste-to-oil-market-to-expand-with-revolutionary-changes-in-the-energy-industry-tmr-301214794.html. [Accessed: 25-Apr-2021].

[16] Nanda, S., and Berruti, F., 2021, “Thermochemical Conversion of Plastic Waste to Fuels: A Review,” Environ Chem Lett, **19**(1), pp. 123–148.
[17] Eriksson, O., and Finnveden, G., 2009, “Plastic Waste as a Fuel - CO2-Neutral or Not?,” Energy Environ. Sci., **2**(9), pp. 907–914.
[18] Dorado, C., Mullen, C. A., and Boateng, A. A., 2014, “H-ZSM5 Catalyzed Co-Pyrolysis of Biomass and Plastics,” ACS Sustainable Chem. Eng., **2**(2), pp. 301–311.
[19] Sikdar, S., Siddaiah, A., and Menezes, P. L., 2020, “Conversion of Waste Plastic to Oils for Tribological Applications,” Lubricants, **8**(8), p. 78.
[20] Banu, J. R., Sharmila, V. G., Ushani, U., Amudha, V., and Kumar, G., 2020, “Impervious and Influence in the Liquid Fuel Production from Municipal Plastic Waste through Thermo-Chemical Biomass Conversion Technologies - A Review,” Sci. Total Environ., **718**, p. 137287.
[21] Cabanes, A., and Fullana, A., 2021, “New Methods to Remove Volatile Organic Compounds from Post-Consumer Plastic Waste,” Science of The Total Environment, **758**, p. 144066.
[22] Oliveira, M. C., and Magrini, A., 2017, “Life Cycle Assessment of Lubricant Oil Plastic Containers in Brazil,” Sustainability, **9**(4), p. 576.
[23] Nabavi-Pelesaraei, A., Bayat, R., Hosseinzadeh-Bandbafha, H., Afrasyabi, H., and Chau, K., 2017, “Modeling of Energy Consumption and Environmental Life Cycle Assessment for Incineration and Landfill Systems of Municipal Solid Waste Management - A Case Study in Tehran Metropolis of Iran,” Journal of Cleaner Production, **148**, pp. 427–440.
[24] Benavides, P. T., Sun, P., Han, J., Dunn, J. B., and Wang, M., 2017, “Life-Cycle Analysis of Fuels from Post-Use Non-Recycled Plastics,” Fuel, **203**, pp. 11–22.
[25] Chhabra, V., Parashar, A., Shastri, Y., and Bhattacharya, S., 2021, “Techno-Economic and Life Cycle Assessment of Pyrolysis of Unsegregated Urban Municipal Solid Waste in India,” Ind. Eng. Chem. Res., **60**(3), pp. 1473–1482.
[26] Energy Weekly News, 2021, “Gale In Context: Environmental Studies - Document - Recycled Plastic and Plastic Waste to Oil Market to Expand with Revolutionary Changes in the Energy Industry: TMR.,” Gale In Context Enviromental Studies [Online]. Available: https://go-gale-com.uidaho.idm.oclc.org/ps/i.do?p=GRNR&u=mosc00780&id=GALE|A651030452&v=2.1&it=r. [Accessed: 25-Apr-2021].
[27] Gracida-Alvarez, U. R., Winjobi, O., Sacramento-Rivero, J. C., and Shonnard, D. R., 2019, “System Analyses of High-Value Chemicals and Fuels from a Waste High-Density Polyethylene Refinery. Part 1: Conceptual Design and Techno-Economic Assessment,” ACS Sustainable Chem. Eng., **7**(22), pp. 18254–18266.
[28] Gopinath, K. P., Nagarajan, V. M., Krishnan, A., and Malolan, R., 2020, “A Critical Review on the Influence of Energy, Environmental and Economic Factors on Various Processes Used to Handle and Recycle Plastic Wastes: Development of a Comprehensive Index,” Journal of Cleaner Production, **274**, p. 123031.
[29] Riedewald, F., Patel, Y., Wilson, E., Santos, S., and Sousa-Gallagher, M., 2021, “Economic Assessment of a 40,000 t/y Mixed Plastic Waste Pyrolysis Plant Using Direct Heat Treatment with Molten Metal: A Case Study of a Plant Located in Belgium,” Waste Management, **120**, pp. 698–707.
[30] Shelley, M. D., and El-Halwagi, M. M., 1999, “Techno-Economic Feasibility and Flowsheet Synthesis of Scrap Tire/Plastic Waste Liquefaction,” Journal of Elastomers & Plastics, **31**(3), pp. 232–254.
[31] Kalargaris, I., Tian, G., and Gu, S., 2017, “Combustion, Performance and Emission Analysis of a DI Diesel Engine Using Plastic Pyrolysis Oil,” Fuel Processing Technology, **157**, pp. 108–115.
[32] Fivga, A., and Dimitriou, I., 2018, “Pyrolysis of Plastic Waste for Production of Heavy Fuel Substitute: A Techno-Economic Assessment,” Energy, **149**, pp. 865–874.
[33] Ghodrat, M., Abascall Alonso, J., Hagare, D., Yang, R., and Samali, B., 2019, “Economic Feasibility of Energy Recovery from Waste Plastic Using Pyrolysis Technology: An Australian Perspective,” Int. J. Environ. Sci. Technol., **16**(7), pp. 3721–3734.
[34] Larrain, M., Van Passel, S., Thomassen, G., Kresovic, U., Alderweireldt, N., Moerman, E., and Billen, P., 2020, “Economic Performance of Pyrolysis of Mixed Plastic Waste: Open-Loop versus Closed-Loop Recycling,” Journal of Cleaner Production, **270**, p. 122442.
[35] Buchner, G. A., Wulfes, N., and Schomäcker, R., 2020, “Techno-Economic Assessment of CO2-Containing Polyurethane Rubbers,” Journal of CO2 Utilization, **36**, pp. 153–168.
[36] Bora, R. R., Wang, R., and You, F., 2020, “Waste Polypropylene Plastic Recycling toward Climate Change Mitigation and Circular Economy: Energy, Environmental, and Technoeconomic Perspectives,” ACS Sustainable Chem. Eng., **8**(43), pp. 16350–16363.
[37] Li, K., Lei, J., Yuan, G., Weerachanchai, P., Wang, J.-Y., Zhao, J., and Yang, Y., 2017, “Fe-, Ti-, Zr- and Al-Pillared Clays for Efficient Catalytic Pyrolysis of Mixed Plastics,” Chemical Engineering Journal, **317**, pp. 800–809.
[38] Predel, M., and Kaminsky, W., 1998, “Pyrolysis of Rape-Seed in a Fluidised-Bed Reactor,” Bioresource Technology, **66**(2), pp. 113–117.
[39] Forster, Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and Van Dorland, R., 2007, “Changes in Atmospheric Constituents and in Radiative Forcing. Chapter 2,” Climate Change 2007. The Physical Science Basis.
[40] OpenLCA, 2019, “The Source for LCA Datasets” [Online]. Available: https://nexus.openlca.org/database/Agribalyse.
[41] Chen, W.-T., Jin, K., and Linda Wang, N.-H., 2019, “Use of Supercritical Water for the Liquefaction of Polypropylene into Oil,” ACS Sustainable Chem. Eng., **7**(4), pp. 3749–3758.
[42] US EPA, R. 09, 2015, “Examples and Resources for Transforming Waste Streams in Communities (#51-100)” [Online]. Available: https://www.epa.gov/transforming-waste-tool/examples-and-resources-transforming-waste-streams-communities-51-100. [Accessed: 18-Nov-2021].
[43] Bureau, U. C., 2021, “IDAHO: 2020 Census,” The United States Census Bureau [Online]. Available: https://www.census.gov/library/stories/state-by-state/idaho-population-change-between-census-decade.html. [Accessed: 29-Sep-2021].
[44] Bureau, U. C., 2019, “Search Results,” The United States Census Bureau [Online]. Available: https://www.census.gov/search-results.html. [Accessed: 22-Apr-2021].
[45] Mirkouei, A., 2016, “Techno-Economic Optimization and Environmental Impact Analysis for a Mixed-Mode Upstream and Midstream Forest Biomass to Bio-Products Supply Chain,” Oregon State University.

[46] Thompson, M. A., Mohajeri, A., and Mirkouei, A., 2021, "Comparison of Pyrolysis and Hydrolysis Processes for Furfural Production from Sugar Beet Pulp: A Case Study in Southern Idaho, USA," Journal of Cleaner Production, p. 127695.

[47] Struhs, E., Mirkouei, A., You, Y., and Mohajeri, A., 2020, "Techno-Economic and Environmental Assessments for Nutrient-Rich Biochar Production from Cattle Manure: A Case Study in Idaho, USA," Applied Energy, **279**, p. 115782.

[48] Mirkouei, A., Haapala, K. R., Sessions, J., and Murthy, G. S., 2016, "Reducing Greenhouse Gas Emissions for Sustainable Bio-Oil Production Using a Mixed Supply Chain," *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers, p. V004T05A031.

[49] Zamora-Cristales, R., Sessions, J., Murphy, G., and Boston, K., 2013, "Economic Impact of Truck–Machine Interference in Forest Biomass Recovery Operations on Steep Terrain," Forest Products Journal, **63**(5–6), pp. 162–173.

[50] Hersh, B., Mirkouei, A., Sessions, J., Rezaie, B., and You, Y., 2019, "A Review and Future Directions on Enhancing Sustainability Benefits across Food-Energy-Water Systems: The Potential Role of Biochar-Derived Products," AIMS Environmental Science, **6**(5), p. 379.

[51] Hersh, B., and Mirkouei, A., 2019, "Life Cycle Assessment of Pyrolysis-Derived Biochar from Organic Wastes and Advanced Feedstocks," *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers, p. V004T05A014.

[52] Almohamadi, H., Alamoudi, M., Ahmed, U., Shamsuddin, R., and Smith, K., 2021, "Producing Hydrocarbon Fuel from the Plastic Waste: Techno-Economic Analysis," Korean J. Chem. Eng.