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Economic Feasibility of Mixed Plastic Waste Pyrolysis Using Twin Reactor System in Northwest Arkansas

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Economic Feasibility of Mixed Plastic Waste Pyrolysis

Using Twin Reactor System in Northwest Arkansas

This thesis was completed by the Pyrolypigs team. I (Kaida Sheets) was the quality control coordinator for the team, and in this section I will discuss my contributions to the team.

In the project, my initial research focused on current collecting methods and procedures both locally and worldwide. I utilized city government websites and contacted municipalities and other collecting sites for questions. Next, I researched current pyrolysis techniques and curated the feed compositions and yield results of the articles I read.

In the design of the commercial process, I utilized Microsoft Visio to present the flow of material for the front end of the process. For the economic analysis, I performed the initial calculations for equipment sizing and equipment costs for the feed hopper, stainless steel shot, oil storage vessels, nitrogen purge, solid storage vessels, 3-phase separator, cyclone banks, mixer, and auger reactor and auger shot heater. From factor cost estimates using the equipment costs, I calculated the total product costs, the fixed capital investment, and the total capital investment.

In writing our report, my areas of focus were on the abstract, executive summary, introduction and background, and process description. In addition to these areas, I was in charge of references. I also contributed to overall review and editing of the report and its format.

In our poster preparation, I focused on the overview, design basis and bench scale pyrolysis sections. I also presented this part of the poster in the poster presentations. In the lab experimentation, I was involved with the feed preparation experiments as well as the first runs of the bench scale pyrolysis.

In the presentation of our project, I created the slides for the introduction and background of our project. I also presented these slides. Additionally, I designed the overall look of the entire presentation to be cohesive and consistent.

Economic Feasibility of Mixed Plastic Waste Pyrolysis

Using Twin Reactor System in Northwest Arkansas

University of Arkansas

Pyrolypigs Team

Task 6: Open Task

Advisors: Dr. Michael Ackerson and Dr. W. Roy Penney

Team Members: Renato Gonzalez, Patricia Means, Carol Rogers, Kaida Sheets, and Hayden Townsend

Table of Contents

***Abstract*— Plastic waste generation is increasing at an unsustainable rate while recycling solutions remain stagnant. As a chemical means of recycling, mixed plastic waste pyrolysis can generate synthetic oil appropriate for use as fuel in power generation from plastic waste that otherwise accumulates in landfills. With the scaling of a commercial plastic pyrolysis process in Northwest Arkansas (NWA) modeled after an operational sawdust pyrolysis unit in Huntsville, Arkansas, economic analysis resulted in 26.3% internal rate of return. Therefore, construction of a commercial mixed plastic-to-fuel pyrolysis plant is economically justified and should be pursued. To effectively implement the proposed design, NWA must utilize involvement from political leaders and the community to effectively make changes to current recycling collection and sortation procedures. Environmental benefits from the implementation of a commercial pyrolysis process for mixed plastics, such as reduction of plastic waste in landfills and oceans, must be emphasized to rally public sentiment to recycle.**

***Keywords—Mixed plastic, pyrolysis, recycling, and economics*.**

I. Executive Summary

Plastic waste continues to be a problem as generation increases without feasible recycling solutions, resulting in a negative impact on marine environments, food and health services, climate change, and even tourism. A robust solution to the problem must address issues such as the poor economics of recycling processes due to high cost of sortation techniques, as well as consumer behavior resulting in lack of participation in plastic recycling. Currently employed solutions to the plastic waste problem do not adequately address all of the challenges that accompany plastic recycling. For example, some types of plastics such as HDPE are recycled individually. However, this requires either sortation of HDPE from recycling streams or consumer sortation of HDPE into a separate stream from other recyclables. Sorting HDPE from a recycling stream is difficult, because the widely used sink-float method for separation of plastics is ineffective in separating HDPE and PP due to their similar densities. Pyrolysis is a feasible option that allows for plastic waste streams to be mostly unsorted. A chemical means of recycling, pyrolysis can take in a feed of plastic types #1 (Polyethylene Terephthalate), #2 (High Density Polyethylene), #4 (Low Density Polyethylene), #5 (Polypropylene), and #6 (Polystyrene) to produce marketable products such as synthetic oil, synthetic gas, and carbon black.

The Pyrolypigs team developed a commercial design for a mixed plastic pyrolysis unit in Northwest Arkansas (NWA). This design was based on an existing sawdust pyrolysis plant in Huntsville, AR, lab experimentation using a bench-scale plastic pyrolysis unit, and existing plastic pyrolysis literature data. The bench-scale provided a proof of concept for plastic pyrolysis of the expected composition of the mixed plastics in NWA. The results of the bench-scale experiments confirmed the yields of pyrolysis and highlighted some potential issues to keep in mind in the commercial design, such as wax buildup in the condenser at lower temperatures. A commercial design was then developed that was similar to the sawdust pyrolysis plant with plastics bought from an existing materials recovery facility (MRF) in NWA.

An economic analysis was performed on the commercial design. Based on purchased equipment costs and factored cost estimates, the fixed capital investment was $6,860,461 with a working capital was $1,210,670. This resulted in a total capital investment of $8,071,131. An economic analysis over a 10-year planning horizon of the pyrolysis process resulted in an internal rate of return (IRR) of 26.3%. This is indicative of a process that could be very lucrative if implemented.

This process, however, must overcome implementation hurdles, such as determining: 1) how collecting and sorting plastics will be implemented by each municipality of NWA; 2) how to initially approach investors, politicians, and NWA citizens in a way that gains support for implementing the process; and 3) how to engage cooperation of the public citizens to participate in the collection process, quelling any fears they have about implementing a new process—especially the fears concerning the environment and process safety.

II. Introduction

A. Background

Plastic waste continues to accumulate in landfills, occupying a decreasing amount of landfill space. Of all plastics that have ever been produced globally, 55% were sent straight to or later discarded to a landfill [1]. According to the United States Environmental Protection Agency (U.S. EPA), plastics in the U.S. comprised 24.5 tonnes (27 million tons; 18% by weight) of the municipal solid waste (MSW) sent to landfills in 2018 [2]. The number of landfilled plastics has increased by over 2 million tons since 2010 (Fig. 1) and plastic recycling has stagnated at around 9.0% (Fig. 2) [2]. Even worse, after end-of-life plastics are landfilled, some take over 1000 years to decompose [3]. Meanwhile, the remaining landfill space in the United States is expected to last for less than 20 years as of 2020 [4]. Ultimately, plastic waste accumulation in landfills is rising, causing landfills to run out of space at an increased rate.

The landfilling problem was further exacerbated by the Chinese government in 2017. Previously, China collected nearly 11% of its total waste as global imports from 2010-2016, and the United States was the third largest exporter of its plastic waste to China in 2016. Unwilling to continue accepting so much waste, China implemented Operation National Sword in 2017, banning imports on non-industrial plastic waste. High income countries producing this “displaced” plastic waste could no longer “recycle” through exports to China and had to dispose of the waste themselves. If a continued 100% ban from 2017 extends to 2030, global estimates of displaced plastic waste will be 110 million tonnes [5]. Before China imposed Operation National Sword, Bryan Staley from the Environmental Research and Education Foundation (EREF) stated in 2015 that the U.S. had about 62 years of remaining landfill capacity [6]. However, the U.S. cannot export non-industrial plastics to China anymore while plastic waste generation continues to increase, so remaining landfill capacity has decreased to around 20 years or less for most regions of the U.S. [4]. Thus, something must be done to remove these mixed plastics from United States landfills.

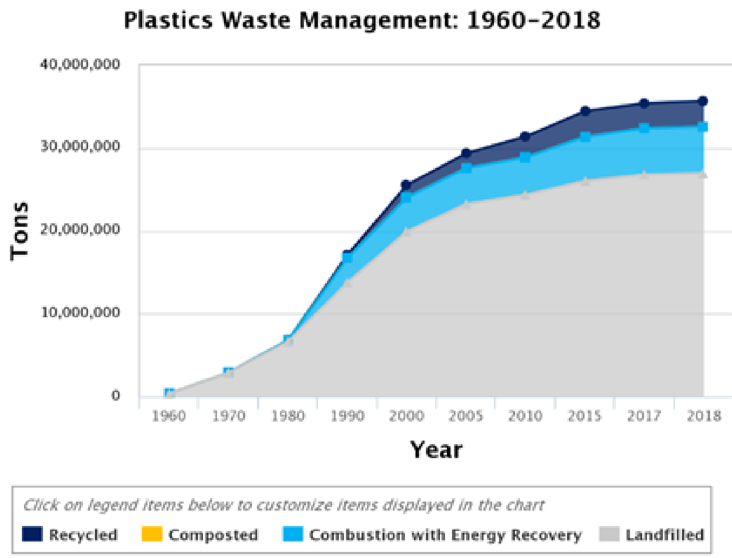


Fig. 1 Plastic Waste Management 1960-2018

Plastic waste also harms marine environments by entering oceans through coastal regions. Fig. 3 depicts 2010 global statistics for the flow of plastic waste from generation to ocean pollution. One third of plastics produced on the coastline were mismanaged ("inadequately managed and littered"), and about a quarter of all mismanaged plastic waste entered oceans [7]. Unfortunately, these numbers only cover what scientists have been able to measure. Another key problem known as the "missing plastics problem" states that the amount of surface ocean plastics is several magnitudes lower than the number of disposed plastics estimated to enter oceans. Main hypotheses for why this problem occurs includes inaccurate measurements, disappearance of microplastics to the ocean floor, and that ocean plastics are washed onto shorelines, buried, and then resurfaced [8][9][10]. Thus, plastic waste has a large impact on marine wildlife. 80% of ocean plastics are estimated to come from land-based sources while the remaining 20% come from marine sources, such as fishing gear [11][12]. Plastic debris harms ecosystems by entangling at least 344 ocean species and entering the digestive tracts of at least 233 ocean species through ingestion, often leading to death. Plastic debris also damages marine ecosystems by collisions with coral reefs, disrupting light penetration and oxygen exchange in ocean sediments, etc. [13].

Recycling could decrease the amount of plastic waste that ends up in landfills and oceans, but current recycling procedures have several key challenges (Fig. 4). Most plastics are landfilled due to poor economics of mixed plastic recycling, consumer behavior, and processing difficulties [14]. Each of these challenges must be addressed to reduce plastic waste accumulation in landfills and in oceans.

Recycling and composting as a percentage of generation

	1960	1970	1980	1990	2000	2005	2010	2015	2017	2018
Paper and Paperboard	17%	15%	21%	28%	43%	50%	63%	67%	66%	68%
Glass	2%	1%	5%	20%	23%	21%	27%	28%	25%	25%
Plastics	Neg.	Neg.	<1%	2%	6%	6%	8%	9%	9%	9%
Yard Trimmings	Neg.	Neg.	Neg.	12%	52%	62%	58%	61%	69%	63%
Lead-acid Batteries	Neg.	76%	70%	97%	93%	96%	99%	99%	99%	99%

Fig. 2 Recycling as Percentage of Generation

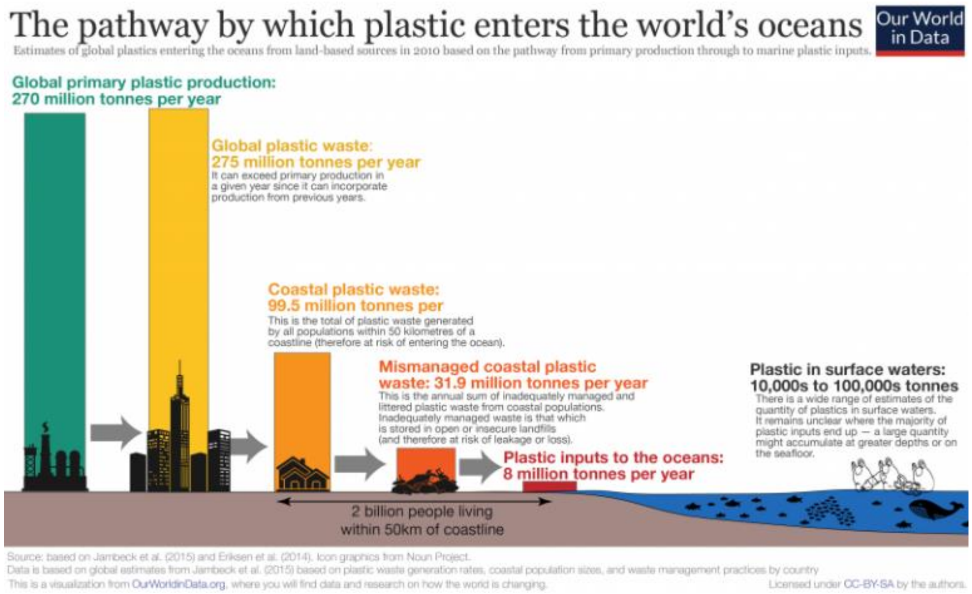


Fig. 3 Pathway for Plastic Waste Entering to Enter Oceans

Economics of mixed plastics recycling significantly hinders the invention and innovation of recycling processes. Despite the indication of recyclability through markers listed at the bottom of #1-7 plastic containers, packaging, cups, plates, etc., these materials are scarcely recycled [2]. These "mixed plastics" are most abundantly composed of non-bottle polyethylene terephthalate (PET/PETE; #1), non-bottle high-density polyethylene (HDPE; #2), polyvinyl chloride (PVC; #3), low-density polyethylene (LDPE; #4), polypropylene (PP; #5), polystyrene (PS; #6), and a catch-all "other" category (#7) for plastics like nylon or plastic blends [15]. Lack of a market for recycling mixed plastics makes the cost of collecting plastic waste outweigh the profit of selling for most cities, deterring them from implementing innovative recycling processes (B. Pugh, personal communication, December 10, 2020).

Waste management companies would also lose revenue by diverting plastics to a recycling facility. Discarded mixed plastic waste, specifically PET, HDPE, LDPE, PP, and PS, comprised 26% of discarded MSW in the United States in 2018 [2]. In Northwest Arkansas (NWA), approximately 2273-2727 tonnes (2500-3000 tons) of trash are landfilled per day, excluding waste from Bentonville and Bella Vista. Some waste comes from border Missouri, Harrison and Jasper, AR, and border Oklahoma (M. Berner, personal communication, March 1, 2021). Therefore, considering most waste (75%) comes from the NWA area and that 17% of this waste is mixed plastic waste

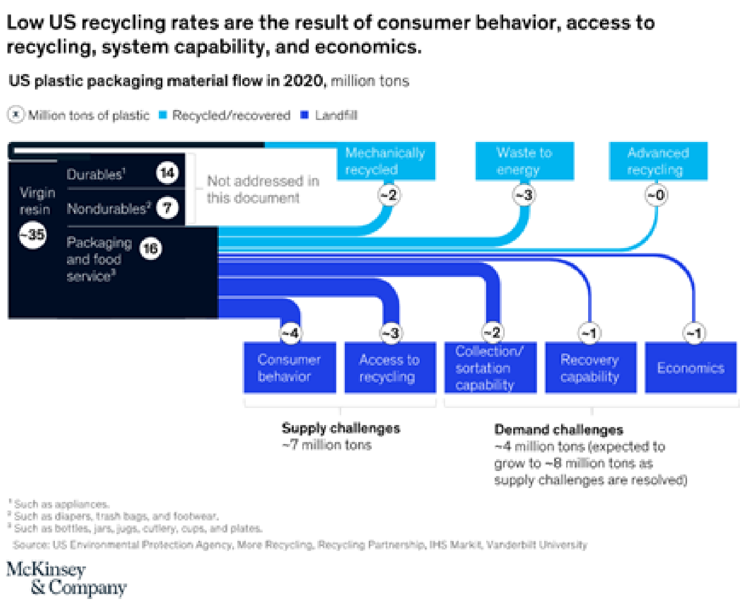


Fig. 4 Recycling Challenges

(accounting for plastic that is incinerated rather than landfilled; estimated as 1/3 of plastic discards), then 290-348 tonnes (319-383 tons) of mixed plastic waste are landfilled per day. With a tipping fee of $38.5/tonne ($35/ton), that accounts for $11,165-13,405 in revenue for the landfill per day. However, one must consider that this is a cost that the city must pay to the landfill to dispose of their mixed plastic waste (M. Berner, personal communication, March 1, 2021).

Culture around recycling and consumer participation does not assist in this problem. Consumer apathy and limited recycling access cause a disconnect from recycling programs, leading to the disposal of many recyclable plastics[14]. To fully address the issue of plastics recycling, a comprehensive plan must include a strategy to increase consumer participation. Culture around recycling and consumer participation does not assist in this problem. Consumer apathy and limited recycling access cause a disconnect from recycling programs, leading to the disposal of many recyclable plastics [14]. To fully address the issue of plastics recycling, a comprehensive plan must include a strategy to increase consumer participation.

B. Team Solution

The Pyrolypigs team has designed a chemical recycling process in Northwest Arkansas (NWA) that reduces the volume of mixed plastic waste entering landfills, works with municipalities to reduce landfilling costs, and increases consumer participation in recycling. NWA was chosen as a design basis for several reasons. First, a pilot-scale pyrolysis unit has already been implemented for sawdust pyrolysis in Huntsville, AR. Secondly, Fayetteville has performed single-stream recycling pilots in the past with readily available data, showing NWA can implement a pilot recycling program. Lastly, the region has already begun efforts to reduce Styrofoam usage through ordinances, indicating that the populace is already conscious about recycling. Therefore, the NWA region could make the necessary changes for the proposed recycling process.

The population of NWA produced an estimated 48,182 tonnes (53,000 tons) of mixed plastic waste in 2016 [16][17]. Current NWA municipalities, namely Fayetteville, Springdale, Rogers, and Bentonville, AR, only recycle #1 and #2 plastic bottles. In 2014, non-bottle plastic waste comprised approximately 17.22% of the MSW stream in Fayetteville, AR [18]. Of these plastics, 14.38% in the MSW stream were landfilled. Other cities in NWA likely have similar statistics.

Many cities attempt cost reduction by placing the responsibility of sorting, and often disposing, of the plastic waste on the consumer that produces the waste. In NWA, city websites specify whether households should dispose of each type of waste through curbside collection, drop-off recycling centers, or directly to MSW management facilities. This methodology does not effectively encourage consumer participation in recycling. Some consumers might not have internet access, especially in rural areas. This results in a lack of participation due to a lack of access to knowledge about the recycling process. Additionally, NWA city websites only specify to thoroughly rinse materials before placing them in a collection bin, but not what "thoroughly rinsed" actually means in the context of recycling (i.e. is some stuck food residue acceptable versus absolutely none at all; should the containers be dried out first before placing them in the collection bin; etc.). For the challenge of increasing consumer participation in the absence of legislative action, a recycling process must be developed with care taken to encourage a change in consumer behavior.

The recycling process in the Pyrolypigs design will be unlike most current recycling processes, which focus on a single plastic type. For example, disposed LDPE bags can be processed into composite lumber, and PET can be processed into polyester fiber [19][20]. Plastic recycling, however, is susceptible to contamination that can turn recyclable plastic into discarded waste. HDPE recycling processes often face issues with PP contamination due to difficulties with sorting out these two plastics. Globally, a sink-float procedure in water is the primary method of plastic separation. However, HDPE and PP have similar densities such that both plastics float. PP can also contaminate recycled HDPE products since both plastics are used for different parts of detergent bottles [21][22]. The Pyrolypigs team solution is robust and can include multiple plastic types without the need to separate pure streams of single plastic types. Therefore, this process significantly reduces mixed plastic in the MSW stream.

Recycling methods typically follow one of two routes. Mechanical recycling retains the chemical structure of the plastics and changes the physical form to achieve a desired use (e.g. PET processing into polyester fibers). Most current recycling methods fall under this category, but differing properties of the various plastics in the MSW stream cause difficulty in determining a single mechanical recycling application without a decrease in quality and costs [14]. Conversely, chemical recycling breaks down the plastics into their molecular and elemental constituents and focuses on energy recovery capabilities. Plastics are composed of dense hydrocarbon polymers that can be thermally cracked to produce oil among other byproduct in a process called thermal pyrolysis. Produced oil quality of pyrolysis ranges from synthetic crude oil to fuel grade oils [23].

Economic advantages of pyrolysis processes come from the high heating value of both the marketable fuel and the gas product, which can be used as an energy source for the process itself. Current pyrolysis processes have shown over 30% internal rate of returns [23]. Along with pyrolysis product marketability, pyrolysis could reduce plastic waste landfilling and plastic waste migration into oceans. Pyrolysis is an ideal solution to depleting mixed plastic waste because all plastics thermally decompose to oils in some quantity. Varying compositions of plastics in a mixed plastic stream will not completely hinder the pyrolysis process.

The Pyrolypigs team has conceptualized a process that produces a synthetic crude oil, which can bring the commercial success of mixed plastic waste pyrolysis to NWA. The purpose of this project is to determine the impact of plastic reduction to landfills, effects on the consumer and NWA municipalities, and economic feasibility of implementing a commercial pyrolysis plant in NWA. Through the construction of a bench-scale pyrolysis unit, the team confirmed design choices and mass balance data. Other key points of focus include expansion of the collection of mixed plastic waste in NWA, development of a plastic preparation procedure, and economic and environmental evaluation of the commercial design.

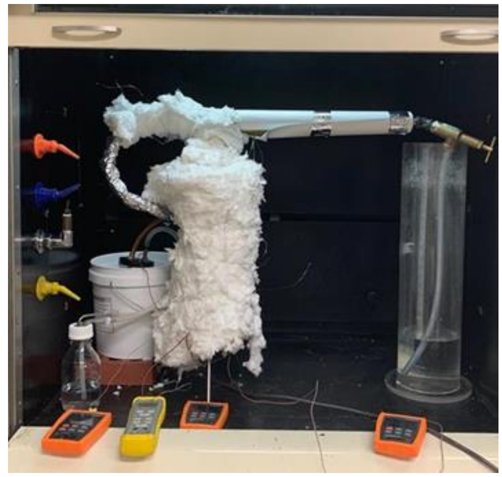
III. Experimentation

A. Bench-Scale Description

In the technical considerations of pyrolysis scaleup, literature data is often scarce or cannot be extrapolated well. For example, the yield of solid, liquid, and vapor products are strongly dependent on the type of reactor, plastic feed, residence time, heating rate, and reactor temperature. These factors highly influences the sizes and types of hydrocarbons produced [23].

A bench-scale pyrolysis reactor was used to demonstrate conceptual feasibility and mass balance information on mixed plastics pyrolysis. The bench-scale reactor was a batch reactor with a volume of approximately 167 cm^3. The reactor was purged with nitrogen and electrically heated to a range of 450-500 ^{0}C. The heating rate and condensing system were varied between each run to observe effect on the product yield and gain insight into commercial design considerations.

During the first experiment, 4ft of copper tubing submerged in cold water condensed the system (Fig. 5), with a reactor temperature of 500 ^{0}C. The reactor was filled to 100% capacity with a feed composition of 12% PET, 20% HDPE, 29% LDPE, 28% PP, and 8% PS. The rate of heating averaged at about 5 ^{0}C/minute. Before the reactor could reach a stable temperature, the pressure relief device was activated (see Fig. 6, depicted right). This indicated that a clog in the condensing system had occurred, necessitating shutdown.



The second run required a few modifications; a different condensing system (Fig. 7) was implemented with a slightly faster reactor heating rate and the reactor was filled to only 60% capacity of a feed composition of 21% PET, 28% HDPE, 40% LDPE, and 11% PS. The condenser setup for the second run is shown in Fig. 7. The heating rate was increased to around 7 ^{0}C/minute. The copper tubing condensing system was insulated and removed from the water bucket. These modifications were implemented in attempt to reduce wax production and eliminate clogging of the condensing coil with pyrolysis wax. The coil was shortened to 3 feet, exiting to a glass jar in a water bucket. This experiment ran until oil stopped dripping from the copper pipe, reaching a stable temperature 500 ^{0}C after an hour. However, most plastics still pyrolyzed to wax. For the third run, the feed had the same composition as run 1. Heating tape was added to the top of the condenser with more insulation further down the copper coil. Most condensing occurred in the

Fig. 5 First Run Condensing System

Fig. 7 Second Run Condensing System

copper pipping that is located inside the glass jar, so ice was added to the water bath to keep the temperature constant.

B. Results

In the first experiment, there was an accumulation of wax sufficient to completely block flow through the system. This wax buildup was located in the connector to the reactor, the condensing system, and the pressure relief system. This reveals an area of concern for a commercial-scale process and should be carefully observed during scale-up at the Huntsville pyrolysis unit. Possible solutions include decreasing the condensation rate and increasing the reactor heating rate, both of which were tested in the following pyrolysis runs. These factors were taken into consideration when determining the cooling medium for the commercial design.

For the second experiment, the heating rate was increased relative to the first experiment. The run achieved a solid yield of 5% and a liquid yield of 68% (Table I). The liquid product was mostly wax, depicted in Fig. 8. The char recovered is depicted in Fig. 9.

An even higher heating rate was implemented in the third run of the bench-scale experiment. A stable temperature was achieved in approximately 30 minutes, as opposed to an hour in the second run. Condenser outlet temperature was set higher than the melting point of the wax (150 ^{0}C). Liquid yield was only 33% and

TABLE I. YIELDS FOR BENCH-SCALE RUNS

	First Run	Second Run	Third Run

contained mostly light sweet crude oil rather than wax.

The results from the bench-scale experiments aided choices for the commercial design.

IV. Commercial Design

A. Process Flow Diagram

The process flow diagram (PFD) for the commercial pyrolysis plant is shown in Fig. 10 and Fig. 11 (page 9). The front end of the process (Fig. 10) is defined from the delivery of sorted plastics from the materials recovery facility (MRF) to the exit point of the feed auger. The back end of the process (Fig. 11) is defined from the entrance of the twin-auger reactor system to the exit of each product stream. Table II (page 10) contains streams for the heat and material balance.

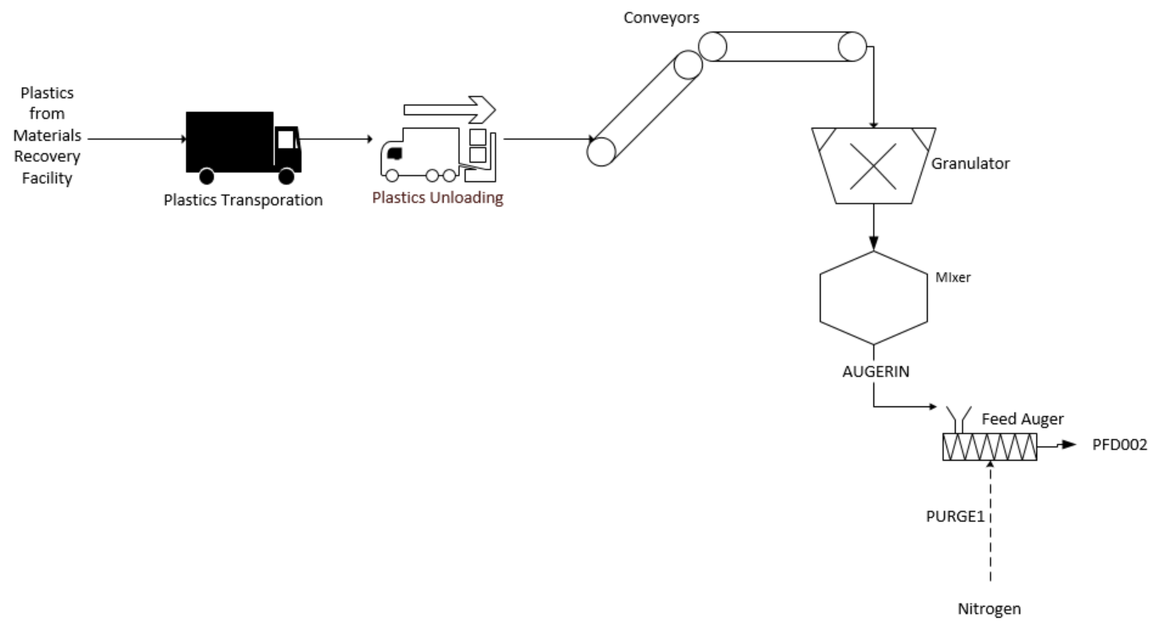


Fig. 10. PFD001

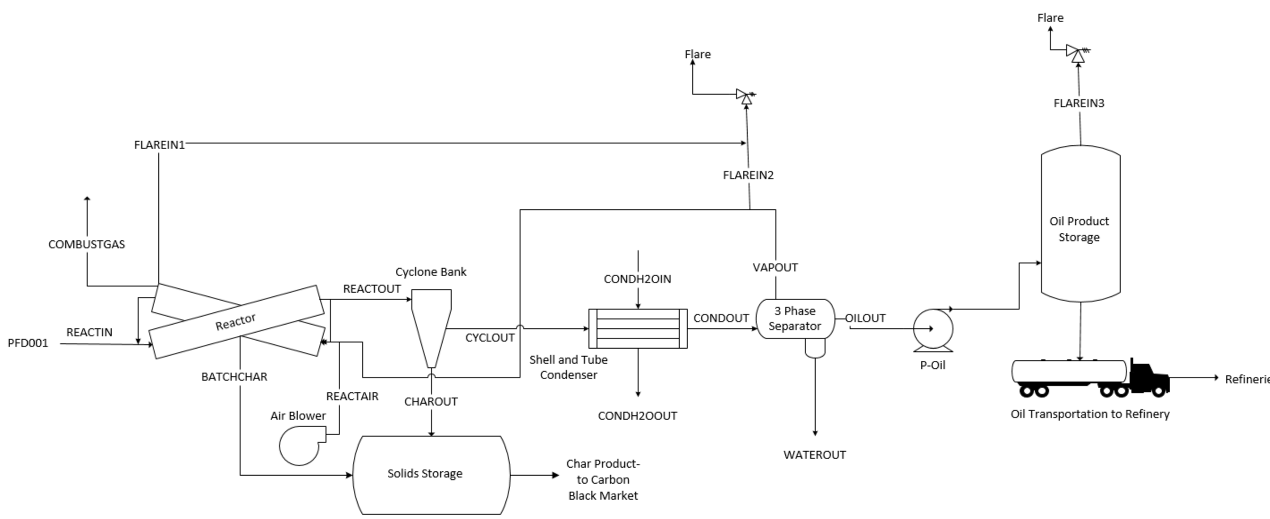


Fig. 11. PFD002

B. *Heat & Material Balance*

TABLE II. STREAM TABLE

	Stream Name	PROCESSIN	MIXERIN	AUGERIN	PURGE1	REACTIN	REACTOUT	CYCLOUT	VAPOUT	WATEROUT	CONDOUT	OILOUT	CHAROUT	CONDH2OIN	CONDH2OOUT	COMBUSTGAS	BATCHCHAR	REACTAIR
Variable	**Units**																	
Pressure	Pa	101325	101325	101325	101325	101325	101325	101325	101325	101325	101325	101325	101325	101325	101325	101325	101325	122003
Temperature	degree C	25	25	25	25	25	500	500	90	90	90	90	500	100	300	500	500	25
Mass Flow	kg/hr	5889	5889	5889	15	5933	5848	5987	1222	503	5987	4318	15	948	948	152	42	5053
Volumetric Flow	m^3/hr	12	12	12	13	50	4239	4239	527	1	1990	5	n/a	2	3	91	n/a	4268
Component Flow Rate	kg/hr																	
PET		845	845	845	0	845	0	0	0	0	0	0	0	0	0	0	0	0
HDPE		1125	1125	1125	0	1125	0	0	0	0	0	0	0	0	0	0	0	0
PP		1588	1588	1588	0	1588	0	0	0	0	0	0	0	0	0	0	0	0
LDPE		1611	1611	1611	0	1611	0	0	0	0	0	0	0	0	0	0	0	0
PS, Plastic		411	411	411	0	411	0	0	0	0	0	0	0	0	0	0	0	0
PS, Expanded		28	28	28	0	28	0	0	0	0	0	0	0	0	0	0	0	0
Oil		0	0	0	0	0	4318	4318	0	0	4318	4318	0	0	0	0	0	0
Water		280	280	280	0	280	503	503	0	503	503	0	0	948	948	0	0	0
Air		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5053
Nitrogen		0	0	0	15	15	15	15	15	0	15	0	0	0	0	0	0	0
Oxygen		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Offgas		0	0	0	0	0	1122	1122	1122	0	1122	0	0	0	0	152	0	0
Char		0	0	0	0	0	42	0	0	0	0	0	42	0	0	0	42	0

C. Process Description

The source of plastic considered of this project is residential and commercial mixed plastic waste of the NWA. Consumers will be expected to do minimal sorting. However, plastics #3 and #7 will go into the garbage bins with other landfilled waste to minimize undesirable products in pyrolysis. Pyrolyzed PVC (#3) produces hydrogen chloride #7 plastics could contain nitrogen content that produces hydrogen cyanide during pyrolysis [24]. Hydrogen chloride and hydrogen cyanide removal would require feed treatment with calcium carbonate or calcium hydroxide powders, increasing raw material costs.

1, #2, #4, #5, and #6 plastics, go into a single-stream recycling bin along with other recyclable materials such as paper, metal, and glass. The cities will collect these materials and transport them to an already existing materials recovery facility (MRF) with the capability to sort mixed plastics into its current waste processing stream. #1 and #2 bottles already have an established, profitable market, so the MRF can continue to sort these plastics and send them to other manufacturers. The pyrolysis plant will coordinate with the MRF to purchase and obtain the remaining plastics through contracted transportation trucks, which will ship non-bottle #1, 2, 4, 5, and 6 plastic bales directly to the pyrolysis plant. These baled plastics will be the input stream for the pyrolysis plant (see Fig. 10).

The design basis for this plant assumes 133 tonnes/day (147 tons/day) of plastic feed is pyrolyzed. The plastic bales will be wrapped in plastic zip-ties made of LDPE as specified by the pyrolysis plant to exclude Nylon or other contaminant plastics. Bales will be loaded via forklift and wheel loader onto a walled conveyor system with a belt velocity of 10 m/hr (33 ft/hr). Bales will be processed to shreds less than 30 cm (1 foot) in length. The shreds will be transported directly to a double cone rotary blender, which can hold shredded feed for up to 30 minutes. The blender maintains uniform feed composition of the incoming bales, though the composition of individual plastics in bales may vary daily. The blender transports plastic shreds into a 9 m^3 (305 ft^3) feed hopper with a 2-ft long opening into the feed auger with the same volume as the reactor augers.

The pyrolysis reactor design is a unique twin-auger system based on the previously mentioned sawdust pyrolysis reactor in Huntsville, AR. Each auger has a volume of 8.2 m^3 (288.5 ft^3) with an inner diameter of 0.762 m (30 in) and length of 17.9 m (58.8 ft). The augers are 10° upward sloping reactors with stainless-steel shot (used for heat transfer) filling 2/3 of volume. The upward slope is necessary because the shot exiting the reactor drops by gravity into the feed end of the shot heater and so the augers are connected at each end with connecting conduits. Shredded plastic feed enters the reactor auger (the front auger) at a rate of 133 metric tons/day (147 tons/day). Pyrolyzed gases travel into the cyclone bank with a little bit of char while some char remains inside the reactor. The return auger (back auger) uses heat from the burned non-condensable syngas stream to heat the shot through a jacket. In this auger, the retained char is removed using a Johnson screen in batches. The

TABLE III. COMMERCIAL DESIGN YIELDS

Basis		Oil		Gas		Char	
Plastic	Weight Fraction of Plastic in Feed	Average Oil Yield in Literature	Weighted Component Average of Oil Yield	Average Gas Yield in Literature	Weighted Component Average of Gas Yield	Average Char Yield in Literature	Weighted Component Average of Char Yield
PET	15.1%	31.0%	4.7%	64.5%	9.7%	4.5%	0.7%
HDPE	20.1%	82.6%	16.6%	9.2%	1.9%	8.2%	1.6%
LDPE	28.7%	85.1%	24.4%	13.2%	3.8%	1.8%	0.5%

designed process will perform pyrolysis at 500 ^{0}C and 1 atm. Predictions for solid, liquid and gas yields were extrapolated from single plastic pyrolysis yields with a reactor temperature range of 450^{0}C-500^{0}C [25][26]. In Table III, the weights and averages are listed along with the calculated product yields.

The cyclone bank removes char from the gas stream, which will be collected for sale to the carbon black market. Gases continue into a shell and tube heat exchanger with a duty of 275.2 kW (940,000 Btu/hr) and an area of 19 m^2 (276 ft^2) to condense into oils, some water, and a non-condensable gas phase. A three-phase separator with a water boot separates each phase into three separate streams. The liquid oil that is stored in fifteen 56 m^3 (14,852-gallon) vessels, enough to hold for 7 days.

At the recommendation of limiting the individual vessel size to be below 75 cubic meters, 15 vessels were chosen to be meet this recommendation. The product is then to be sold into the crude oil market. The following assumptions apply for calculations in this plant:

1. Continuous production

2. 77% of product will be liquid

3. 20% of product will be non-condensable gas

4. 3% of product will be solid

5. All of the solid will be char and no wax is produced

6. Half of the char will be carried with the gas stream into the cyclone; the other half will remain in the reactor

7. The moisture content of the plastic waste feed is too low to justify a drying/pneumatic transport system

8. Plastic does not begin pyrolyzing until 500 C

9. No leaks in system

10. Mass of water entering system is 5 wt% of the total plastics entering the system

11. No contamination of product inlet stream

V. Economics

A. Capital Costs

Equipment costs were split up between front end equipment (Table IV) and pyrolysis equipment (Table V).

TABLE IV. FRONT END EQUIPMENT COSTS

Purchased Equipment: Front End		
Equipment	Sizing	Cost
Shredder	1.56 kg/hr	$ 74,000
Mixer	78.31 cf	$ 37,000
Conveyor	400 ft	$ 60,000
Feed Hopper	12 cum	$ -
Forklifts	N/A	$ 60,000
Wheel Loader	100 hp	$ 45,000
Dust Collection	750 cf/min	$ 4,000
Total		**$ 280,000**

TABLE V. PYROLYSIS EQUIPMENT COSTS

Purchased Equipment: Pyrolysis		
Equipment	Sizing	Cost
Augers	169.6 cf	$ 345,000
Stainless Steel Shot	577 cf	$ 281,589
Nitrogen Generators	14 kg/hr	$ 31,000
Cyclone Bank	5622.5 kg/hr	$ 10,125
Condenser	19 squared meters	$ 6,903
3 phase separator with water boot	Oil volume: 360 cum Water volume: 72 cum	$ 78,239
Flare System	Height: 40 ft Diameter: 1 ft	$ 73,007
Oil Storage Vessel	56 cum	$ 318,781
Storage Vessel	8.46 cum	$ 17,000
Pumps	45 kW	$ 9,205
Total		**$1,170,849**

Capital costs (Table VI) of the commercial plant use factored cost estimates.

B. Total Product Costs

The process requires 8 operators per shift for total number of 34 operators. At $40,000 per year salary, operating labor costs $1,371,429. Utilities for the commercial design are composed of three expenses. Electricity is based on power requirement calculations for equipment. Steam and wastewater treatment are based on the flowrates of steam and water in the process. The steam required to cool the gas stream from the shell and tube heat exchanger is based on ASPEN simulation. The wastewater stream is water exiting from the Three-Phase Separator. The total product costs are included in Table VII.

TABLE VI. CAPITAL COSTS

Capital Cost			
Type of Cost	**Front End**	**Pyrolysis**	**Total**
Equipment Cost	$ 280,000	$ 889,260	$ 1,169,260
Delivered-Equipment Cost	$ 308,000	$ 978,186	$ 1,286,186
Installation	$ 126,000	$ 425,152	$ 551,152
Instrumentation and Control	$ 50,400	$ 320,134	$ 370,534
Piping	$ 44,800	$ 604,697	$ 649,497
Electrical	$ 99,423	$ -	$ 99,423
Building	$ 70,000	$ 160,067	$ 230,067
Yard	$ 42,000	$ 88,926	$ 130,926
Service	$ 112,000	$ 622,482	$ 734,482
Total Direct Costs	**$ 1,132,623**	**$ 4,088,904**	**$ 5,221,527**
Eng. and Supervision	$ 92,400	$ 293,456	$ 385,856
Construction	$ 109,200	$ 364,597	$ 473,797
Legal	$ 11,200	$ 35,570	$ 46,770
Contractor's fee	$ 47,600	$ 195,637	$ 243,237
Contingency	$ 98,000	$ 391,274	$ 489,274
Total Indirect Costs	**$ 358,400**	**$ 1,280,534**	**$ 1,638,934**
Fixed Capital Investment	**$ 1,491,023**	**$ 5,369,438**	**$ 6,860,461**
Working Capital	**$ 263,122**	**$ 947,548**	**$ 1,210,670**
Total Capital Investment	**$ 1,754,145**	**$ 6,316,986**	**$ 8,071,131**

TABLE VII. TOTAL PRODUCT COSTS

Category	Cost, $	
Raw Materials	$	20,874
Operating Labor	$	1,360,000
Operating Supervision	$	204,000
Utilities		
-Water Cooling	$	-
-Water Process	$	-
-Electricity	$	99,423
-Fuel	$	-
-Refrigeration	$	-
-Steam	$	35,001
-Waste Treatment/Disposal	$	2,241
Maintenance/Repairs	$	843,337
Operating Supplies	$	126,501
Laboratory Charges	$	204,000
Royalties	$	-
Catalysts and Solvents	$	-
Total Variable Production Costs	**$**	**2,895,378**
Taxes (Property)	$	140,556
Financing (Interest)	$	-
Insurance	$	70,278
Rent	$	-
Depreciation	$	-
Total Fixed Charges	**$**	**210,834**
Plant Overhead Costs	**$**	**1,685,136**
Administrative Costs	$	204,000
Distribution & Marketing Costs	$	-
Research & Development Costs	$	-
Transportation Costs	$	2,087
General Expenses Total	**$**	**206,087**
Total Product Cost (w/out depreciation)	**$**	**4,997,435**

C. *Revenue*

Revenue is calculated from oil and char produced (Table VIII). Oil is the major source of revenue, but enough char is produced that it can be sold for profit. The oil price is based on current crude oil prices. A better approximation is hard to estimate due to fluctuating prices, but the value of the produced oil is fairly high for two reasons. The oil is light, having a low viscosity [25], and the oil is sweet, having a low sulfur content, because plastics and their additives typically do not have sulfur [27]. Light, sweet crude oils have great market value- an average of $65/barrel [28]. The char price is set at $0.66/kg, a conservative estimate as the market for recovered carbon black is expected to grow in the next decade [29].

Table VIII. Revenue

Char	
Cost of char, $/kg	$0.66
Yield, kg/year	736,891
Annual revenue, $/year	$486,348
Oil	
Cost of crude oil,	

D. *Economic Analysis*

Economic analysis of the commercial process design must address all stages from the retrieval of the plastics to the product market. At the beginning process battery limits, plastics are purchased from an existing, regional MRF. The cost of plastics to purchase from the MRF were quoted by a landfill supervisor at a value of $142/ton (M. Berner, personal communication, March 26, 2021). This cost will cover the baling and delivery fee to the commercial unit by the MRF as well as the extra payment to allow the MRF to return a profit. In areas where uncertainty was present, such as with the interest rate on the loan and the purchase price of the reactor augers, conservative estimates were chosen.

Depreciation was calculated using 5-year Modified Accelerated Cost Recovery System (MACRS), and the combined state and federal taxation rate was 27%. Construction and equipment assembly will take an estimated 12-18 months between building in shop, equipment installation, utilities sourcing, permit approval[1] and facility construction. Additionally, certain equipment such as forklift and wheel loader were separated from the equipment cost since the cost would be yearly due the equipment being rented. The price for renting the forklift and wheel loader was estimated to be $5,000/month and $3,750/month, respectively. Bulk bags were also separated from the equipment cost. This is due to bulk bags being a yearly cost for storage (M. Berner, personal communication, March 26, 2021). Bulk bags were priced for $20 per bag with a maximum allowable weight of 2000 lbs. Land costs were based on an average property costs as of March 2021 in industrial Springdale, AR. This area was chosen as a central location

[1] See Health, Safety, and Environmental Regulations section to read more on required permits for a pyrolysis plant

to the municipalities of NWA. For ten acres of land, the property costs are approximately $160,000.

The results of a 10-year economic analysis are shown in Table IX. The internal rate of return (IRR) is 26.3%, indicating that investment in this process will yield favorable returns with conservative estimates. This is consistent with the historical returns from other pyrolysis companies [30].

TABLE IX. ECONOMIC ANALYSIS

Year	0	1	2	3	4	5	6	7	8	9	10
1.Fixed capital investment	$ 7,142,051										
2. Working capital	$ 1,210,670										
3. Salvage value	$ 217,627										
4.Total capital investment	$ 8,352,720										
6. Start-up cost	$ 714,205										
7. Operating rate. % of capacity per year	0%	50%	90%	100%	100%	100%	100%	100%	100%	100%	100%
Total cost at year 0	**$9,226,925**										
Production of oil per year (barrels oil/year)	-	134,765	242,576	269,529	269,529	269,529	269,529	269,529	269,529	269,529	269,529
Price per unit ($/barrel oil)		$ 65	$ 65	$ 65	$ 65	$ 65	$ 65	$ 65	$ 65	$ 65	$ 65
Production of Char per year (kg/year)		368,446	663,202	736,891	736,891	736,891	736,891	736,891	736,891	736,891	736,891
Price per unit ($/kg char)		$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66
8.Annual sales	$ -	$ 9,002,879	$ 16,205,181	$ 18,005,757	$ 18,005,757	$ 18,005,757	$ 18,005,757	$ 18,005,757	$ 18,005,757	$ 18,005,757	$ 18,005,757
9. Annual manufacturing cost											
a. Raw materials	$ -	$ 3,652,950	$ 6,575,310	$ 7,305,900	$ 7,305,900	$ 7,305,900	$ 7,305,900	$ 7,305,900	$ 7,305,900	$ 7,305,900	$ 7,305,900
b. Labor	$ -	$ 1,577,143	$ 1,577,143	$ 1,577,143	$ 1,577,143	$ 1,577,143	$ 1,577,143	$ 1,577,143	$ 1,577,143	$ 1,577,143	$ 1,577,143
c. Utilities	$ -	$ 136,666	$ 136,666	$ 136,666	$ 136,666	$ 136,666	$ 136,666	$ 136,666	$ 136,666	$ 136,666	$ 136,666
d. Maintenance and repair	$ -	$ 1,356,990	$ 1,356,990	$ 1,356,990	$ 1,356,990	$ 1,356,990	$ 1,356,990	$ 1,356,990	$ 1,356,990	$ 1,356,990	$ 1,356,990
f. Operating supplies	$ -	$ 203,548	$ 203,548	$ 203,548	$ 203,548	$ 203,548	$ 203,548	$ 203,548	$ 203,548	$ 203,548	$ 203,548
g. Laboratory Costs	$ -	$ 236,571	$ 236,571	$ 236,571	$ 236,571	$ 236,571	$ 236,571	$ 236,571	$ 236,571	$ 236,571	$ 236,571
h. Property taxes and insurance	$ -	$ 214,262	$ 214,262	$ 214,262	$ 214,262	$ 214,262	$ 214,262	$ 214,262	$ 214,262	$ 214,262	$ 214,262
j. Plant overhead	$ -	$ 1,104,000	$ 1,104,000	$ 1,104,000	$ 1,104,000	$ 1,104,000	$ 1,104,000	$ 1,104,000	$ 1,104,000	$ 1,104,000	$ 1,104,000
Other		$ 431,748	$ 122,000	$ 122,000	$ 122,000	$ 122,000	$ 122,000	$ 122,000	$ 122,000	$ 122,000	$ 122,000
10. Total of (9)	**$ -**	**$ 8,913,878**	**$ 11,526,490**	**$ 12,257,080**	**$ 12,257,080**	**$ 12,257,080**	**$ 12,257,080**	**$ 12,257,080**	**$ 12,257,080**	**$ 12,257,080**	**$ 12,257,080**
11. Annual general expenses											
a. Administration	$ -	$ 394,286	$ 394,286	$ 394,286	$ 394,286	$ 394,286	$ 394,286	$ 394,286	$ 394,286	$ 394,286	$ 394,286
b. Distribution and marketing	$ -	$ 267,416	$ 345,795	$ 367,712	$ 367,712	$ 367,712	$ 367,712	$ 367,712	$ 367,712	$ 367,712	$ 367,712
c. Research and development	$ -	$ 445,694	$ 576,324	$ 612,854	$ 612,854	$ 612,854	$ 612,854	$ 612,854	$ 612,854	$ 612,854	$ 612,854
12. Total of (11)	**$ -**	**$ 1,107,396**	**$ 1,316,405**	**$ 1,374,852**	**$ 1,374,852**	**$ 1,374,852**	**$ 1,374,852**	**$ 1,374,852**	**$ 1,374,852**	**$ 1,374,852**	**$ 1,374,852**
Total product cost		$ 10,021,274	$ 12,842,894	$ 13,631,932	$ 13,631,932	$ 13,631,932	$ 13,631,932	$ 13,631,932	$ 13,631,932	$ 13,631,932	$ 13,631,932
Annual Operating Income		$ (1,018,395)	$ 3,362,287	$ 4,373,825	$ 4,373,825	$ 4,373,825	$ 4,373,825	$ 4,373,825	$ 4,373,825	$ 4,373,825	$ 4,373,825
Annual Depreciation		$ 1,428,410	$ 2,285,456	$ 1,371,274	$ 822,764	$ 822,764	$ 411,382	$ -	$ -	$ -	$ -
Total Operating Expenses		$ 11,449,684	$ 15,128,351	$ 15,003,205	$ 14,454,696	$ 14,454,696	$ 14,043,314	$ 13,631,932	$ 13,631,932	$ 13,631,932	$ 13,631,932
Income Before Tax		$ (2,446,805)	$ 1,076,831	$ 3,002,552	$ 3,551,061	$ 3,551,061	$ 3,962,443	$ 4,373,825	$ 4,373,825	$ 4,373,825	$ 4,373,825
State+Federal Tax		$ (636,169)	$ 279,976	$ 780,663	$ 923,276	$ 923,276	$ 1,030,235	$ 1,137,195	$ 1,137,195	$ 1,137,195	$ 1,137,195
Net After Tax Income		$ (1,810,636)	$ 796,855	$ 2,221,888	$ 2,627,785	$ 2,627,785	$ 2,932,208	$ 3,236,631	$ 3,236,631	$ 3,236,631	$ 3,236,631
Annual Cash Flow	$ (8,512,720.34)	$ (382,226)	$ 3,082,311	$ 3,593,162	$ 3,450,550	$ 3,450,550	$ 3,343,590	$ 3,236,631	$ 3,236,631	$ 3,236,631	$ 3,236,631
Annual Discounted Cash Flow	$ (8,512,720.34)	$ (302,676.97)	$ 1,932,837.01	$ 1,784,247.00	$ 1,356,831.24	$ 1,074,447.57	$ 824,459.63	$ 631,988.12	$ 500,458.77	$ 396,303.31	$ 313,824.68
IRR	**26.28%**										

VI. CONCLUSIONS

Mixed plastic waste (non-bottle PET, HDPE, LDPE, PP, and PS) in Northwest Arkansas can be effectively managed by implementing a commercial mixed plastic-to-fuel pyrolysis plant. The proposed process has been calculated to be extremely economical, with an internal rate of return of 26.3%. Therefore, constructing a commercial mixed plastic-to-fuel pyrolysis plant is economically justified and should be pursued.

A bench-scale demonstration of the pyrolysis of mixed plastics was performed to demonstrate conceptual feasibility of this process and obtain mass balance information. Several runs were performed at varied heating and cooling rates to determine effects on product composition. Ideal design specification for scale-up to pilot and commercial designs includes minimal to no wax production by utilizing a high reactor heating rate and setting the minimum coolant temperature to 150 ^{0}C. Heat and insulation must be utilized to ensure that wax is unable to form and block flow in the unit. Liquid yields ranged from 33-68% and solid yield remained less than or equal to 5%; leftover yield was uncollected gaseous products that did not condense.

When scaling up mixed plastic pyrolysis to a commercial design, several hurdles must be addressed to fully implement this process. Collecting and sorting the mixed plastics through a materials recovery facility and contracting the transport of plastics from the facility to the pyrolysis plant are key parts of the front end. Currently, the cities of Bentonville and Bella Vista use a separate materials recovery facility to sort their recyclables. The community relations plan will be key to gaining cooperation from Bentonville and Bella Vista to join the remainder of NWA and collect all recyclables at one facility, resulting in an increase in available mixed plastics to feed the pyrolysis unit.

Another issue to be addressed is the possibility of hesitance from investors. Plastics-to-fuel pyrolysis is a form of chemical recycling, which is still a relatively new commercial-scale technology compared to traditional mechanical recycling. This might make new investors skeptical when presented with the idea of implementing this process in Northwest Arkansas. However, showing that the process is profitable with an IRR of 26.3%, even with taking out a loan for all initial costs and applying conservative estimates, should reassure investors and gain their support.

Environmentally active citizens in NWA might be hesitant to endorse this process due to undesirable greenhouse gas emissions. Pyrolyzing mixed plastics results in an oil product, which would emit greenhouse gases when refined and burned. Emissions would also be produced when burning the syngas. In order to rally public sentiment, emphasis of the environmental benefits of removing plastics from entering landfills and oceans is crucial to provide justification for implementing this process. The defined procedure for commercial pyrolysis is inherently more robust in handling plastic waste than typical recycling procedures, due to the capability of the pyrolysis unit to handle a more diverse feed. Therefore, commercial pyrolysis will allow for more efficient reduction of environmental plastic waste compared to current recycling procedures.

Consumer recycling behavior will be difficult to change due to lack of interest in changing how plastics are currently handled of in the household. The community relations plan outlines specific steps that will be taken to combat this hesitance, but cooperation from politicians in each municipality will be critical in spreading the word as to why consumers should participate in recycling and change how they currently recycle. Effectively conveying the long-term environmental benefits for the community that would accompany the implementation of a commercial unit for the pyrolysis of mixed plastics is again critical to gain public support.

Lastly, initial communication detailing the implementation of this process to politicians, investors, product buyers, etc. will be difficult and ineffective without further analysis and testing of the commercial process. Future work that could make this communication more effective includes: 1) further analysis of pyrolysis products from bench-scale demonstration, 2) further testing and optimization of the Huntsville pilot-plant for the pyrolysis of a mixed plastic feed, and 3) gaining more support and feedback from municipal waste facilities and material recovery facilities in NWA for the implementation of this process.

VII. Health, Safety, and Environmental regulations

The commercial pyrolysis plant must comply with health, safety, and environmental regulations both at the state and federal level. All regulations and safety concerns that have been considered are outlined below.

A. Equipment Operation Safety

1) Front End of Process

The front end of this process is expected to contain dust accumulation as one of the main hazards, namely for the shredder and solids mixer. Two shredders will be used so that, while one is being cleaned with a dust collector, the other can keep continuous operations going. The mixer will be closed-top to prevent plastics from leaving the mixer, and occasional puffs of air will remove plastic shred and dust buildup on the walls and top of the mixer.

Accumulated dust from dust collector will be fed into the feed auger using a pipe chute so as to prevent dust dispersion. To limit oxygen content available to the dust, the chute will be angled to feed directly into the nitrogen purge of the feed auger.

Lastly, plastic dust is considered a hazard by the Occupational Safety and Hazard Administration (OSHA) and the National Fire Protection Agency (NFPA). Therefore, all hazard identification and risk assessments must consider the components of the dust explosion pentagon: 1) combustible dust, 2) ignition source, 3) oxygen in the air, 4) dispersion of dust particles, and 5) confinement of the dust cloud. Electrical wiring at the front end must be Class II (for dust hazards) to comply with NFPA 70 Article 500.

Other hazards for the front end of the process must be addressed as follows:

1. Heavy equipment and bales are used for the loading process. Those operating the forklifts and front loader must remain in a restricted area away from workers that are walking around the facility.

2. Conveyors will be open top with walls on the side to keep plastics from falling off while maintaining visibility of the feed line. Conveyors are also utilized for feeding the shredder so as to prevent workers from going near the sharp blades in the shredder.

3. The mixer will also be closed-top for general worker safety.

4. The feed auger will retain heat from the reactor during the end of start-up and steady-state operations. Additionally, the nitrogen purge inside the feed auger contains low oxygen conditions and must be purged with air before maintenance should ever be performed on the feed auger.

2) Twin-Auger Reactor and Syngas Burner

The reactor will operate at 500 ^{o}C, so it will remain insulated with a jacket to prevent heat loss and comply with standards for general worker safety (high temperature equipment is defined as equipment operating at greater than or equal to 50 ^{o}C). The reactor requires nitrogen purge prior to start-up so as to prevent an explosion hazard in the return auger leg when fuel gases are combusted for heating the stainless-steel shot. Tight connections will ensure no gas escape, especially hydrogen, and the augers will be connected in a way that prevents backflow of gases from one auger into the other. A pressure relief device on the reactor will be connected to a ground flare in case the system over pressurizes.

The syngas burner will combust all non-condensable gases inside a reactor jacket to heat the stainless-steel shot inside the return auger. Remaining heat from the burner could be diverted to steam generation for the "cool" side of the shell-and-tube condenser or used for power recovery. However, this process will currently divert the gases that are not used to heat the shot into the ground flare system. The burner will be located away from the rest of the equipment in the process and will be properly insulated to lower risk of explosions in the case of dust dispersion or leaks from pieces of equipment. Gas alarms will monitor oxygen, hydrogen, and methane levels to alert workers of any potential gas leaks.

Without proper selection for the material of construction, the burner and reactor will expand very quickly. This is due to rapid expansion of produced gases from pyrolysis in the reactor and combustion of the syngas for the burner. These pieces of equipment will also be operating at high temperatures with the reactor approaching 500 ^{o}C at steady-state and the burner reaching 1000 ^{o}C. Therefore, these pieces of equipment must be constructed from metals that can withstand and limit rapid expansion as well as high temperatures (e.g. stainless steel).

3) *Back End of Process*

All equipment located at the back end of the process will comply with standards for general worker safety regarding high temperatures. The condenser will use steam on the "cool" side and the condenser outlet will be insulated; both of these measures are to prevent wax buildup. A pressure relief device will also be located on the condenser in case wax buildup does occur. Emergency shutdown controllers will stop all operation in the case that wax buildup triggers the pressure relief device. Additionally, the three-phase separator will contain insulation and a pressure relief device in case the vessel overpressures from syngas production.

Storage vessels for the oil product will be located indoors and will also contain pressure relief devices. Multiple vessels will be utilized so that the process can remain continuous while refinery trucks pick up the oil from other storage vessels that are not currently being filled. Upon start-up and oil transfer into refinery trucks, valves will open at the top of the vessels to ensure that the vessel does not over pressurize from displaced air or under pressurize from displaced oil. The burner has been discussed in previous sections.

B. *Environmental Regulations*

1) *Air Quality*

The commercial pyrolysis plant will obtain air quality permits through the Arkansas Department of Environmental Quality (ADEQ). This process is expected to take 5-6 months, including application submission, technical review by environmental engineers, draft review with all involved parties, and public comments. Upon review of federal regulations, it appears that EPA Title 40 Part 60 Protection of Environment regulations subparts VV (*Standards of Performance for Equipment Leaks of VOC in the Synthetic Organic Chemicals Manufacturing Industry for which Construction, Reconstruction, or Modification Commenced After January 5, 1981, and on or Before November 7, 2006*) and RRR (*Standards of Performance for Volatile Organic Compound Emissions From Synthetic Organic Chemical Manufacturing Industry (SOCMI) Reactor Processes*) will likely apply to this process.

Usually there are three levels of permits: registrations, minor source permitting, and Title 5 permitting through the EPA. Approval of these permits may be broken up into multiple parts with one permit allowing for construction and other permits allowing for operation. However, permits in Arkansas perform all parts at once, so the location and design will be picked out, shown to ADEQ, and approved for permitting before construction of the facility can begin (J. Smith and C. Riley, personal communication, March 26, 2021).

2) *Water Quality*

While a wastewater permit through ADEQ will be unnecessary for our process due to low amounts of wastewater production, the requirements for wastewater set by the municipality of Springdale, AR must be met by this facility. Additionally, stormwater permits will be required for both construction and industrial operation for any equipment expected to be outside—these permits are easy to obtain as they only take a few weeks to get approved. This facility is expected to gain a no-exposure exclusion to the industrial stormwater general permit since the equipment will be located inside a building. (J. Sears, personal communication, March 26, 2021)

3) *Solids*

This facility is somewhat treated as a materials recovery facility, so it would be exempt from solid waste permitting. However, a waste determination must be performed on the solid plastic waste entering the facility by looking at safety data sheets for various plastics and researching pyrolysis reaction products in depth (A. Kreps, personal communication, March 26, 2021).

The pyrolysis plant will only be producing char as a solid waste product, and it will be sold directly in the carbon black market as a low-grade carbon black, so the Pyrolypigs team has not identified the char as hazardous waste. However, if operations show that hazardous waste is being produced, then the facility will immediately comply with the regulations concerning hazardous waste. In general, the process will involve either further processing into carbon black or sending waste to a hazardous waste facility, obtaining an EPA identification number, Resource Conservation and Recovery Act compliance, etc. (L. Cross, personal communication, March 26, 2021).

C. *Waste Generation Considerations*

In pyrolysis, waste generation must be considered as soon as the products leave the reactor. Pyrolysis yields gaseous products (condensable and non-condensable) and solid products, such as wax and char. Based on the literature, char mainly contains carbon and any additives from the plastics that could not be turned into hydrocarbons [31]. Char as a result of HDPE pyrolysis is mostly comprised of volatile and carbon products with less than 5 wt% moisture and ash [32]. Pyrolysis of multiple plastics, especially if they contain HDPE, is predicted to have similar moisture and ash content, but this would be researched further before process implementation. Char produced from pyrolysis could potentially be used as an asphalt binder [33]. Wax is comprised of mostly long paraffin hydrocarbons [34]. Some companies were successful in patenting processes by which paraffin wax can be derived from plastic pyrolysis[35][36].

However, in a 2015 study, thermal decomposition (pyrolysis without a catalyst) plastic-to-fuel companies disposed of the char and wax that came out of the reactor into a landfill [31]. The produced char was 5-8% by weight of the incoming feedstock and most companies did not report any wax production. While one plastics-to-fuel company based in Georgia, did report wax production, it was only 3-10% by weight of incoming feedstock [31]. Based on the experiments performed by the Pyrolypigs team, this could be the result of a slow heating rate to maximize liquid production (and consequently wax) or an efficient condensing system that cools the product too quickly into a wax. Regardless, the market for char and wax produced from pyrolysis is currently rather small. Therefore, due to high carbon content, the Pyrolypigs team will sell the char as a low-grade carbon black in the carbon black market. If the char is identified as hazardous waste during research and development prior to first-year operation, the char will be further processed into carbon black or treated as hazardous waste (see VII section B. *Environmental Regulations*)

Small amounts of water vapor will be produced due to combustion, a direct result of oxygen liberation from PET pyrolysis. A three-phase separator will separate any produced water, non-condensable gases, and light sweet synthetic crude oil. The water will collect in a water boot attached to the separator and will eventually be pumped to a water storage tank. The tank water will be tested for various contaminants and sent to a wastewater treatment plant.

Lastly, the non-condensable gas stream will be utilized for energy recovery. As can be seen in the PFD, the Pyrolypigs team plans to burn the non-condensable gases and recover the energy using a fuel gas system. The non-condensable gas stream is mostly comprised of hydrogen and lightweight hydrocarbons, giving it a similar heating value to natural gas. Therefore, natural gas is capable of use for process start-up to heat the return auger of the reactor. However, once enough non-condensable gas products accumulate in the system, the heating of the reactor should be self-sufficient with the fuel gas system.

It is assumed that the burner will combust the hydrogen and lightweight hydrocarbons into (mostly) carbon dioxide and water. These exhaust gases will be vented to the atmosphere in a way that follows an air quality permit outlined by the Arkansas Department of Environmental Quality (see VI section B. *Environmental Regulations*). Each pressure relief device that is attached to equipment will run to a ground flare, which will burn the released gases if the system over pressurizes.

VIII. Community Relations Plan

Cities in NWA have already launched several programs to address this growing plastic waste problem. The city of Fayetteville started the “Recycle Something” initiative, with the goal of diverting at least 40% of all waste in the landfill by the year 2027 [37]. Fayetteville also imposed a city-wide ban of EPS from establishments serving food and/or drinks according to the City of Fayetteville website. It is evident that municipalities are realizing the need for innovative solutions for the mixed plastic waste problem in NWA.

There are several issues in the current recycling and waste management procedures in NWA that may hinder the implementation of a commercial process for the pyrolysis of mixed plastics. Most importantly, the current sortation and collection procedures for plastic waste, defined on local recycling center websites, do not adequately separate the plastics needed for the pyrolysis unit. Fayetteville, Springdale, Rogers, and Bentonville only recycle #1 and #2 plastic bottles out of bulk plastic waste, and the remaining plastics are sent to landfills. The city of Fayetteville currently collects recyclables in two streams; one stream includes cardboard, glass, aluminum, and recyclable papers, and the other includes #1 and #2 plastic bottles. This two-stream process is ineffective in encouraging community participation due to complex household sorting procedures. Another issue in current NWA recycling procedures is the hesitance of the Bentonville and Bella Vista communities to send their recyclables to the local central materials recovery facility, due to political disagreements (M. Berner, personal communication, March 1, 2021). This issue decreases the quantity of plastics sent to the recovery facility, which would in turn decrease the amount of plastic feed available for the proposed commercial pyrolysis unit.

The plan proposed by the Pyrolypigs team for the commercial pyrolysis of mixed plastic waste in NWA addresses these issues through community involvement in the implementation of new recycling and waste collection procedures. Residents of NWA would be required to modify the way that they recycle plastics in the home in order to implement the proposed single stream recycling process. Households would now recycle cardboard, glass, aluminum, and recyclable papers along with all plastics #1, #2, #4, #5, and #6 in the same bin. Plastics #3 and #7 would go into garbage bins along with other waste to be sent to landfills. It will take time and effort for the community to adopt new recycling procedures, so this plan will likely meet initial public resistance. Therefore, advertisement of environmental waste reduction benefits and the simplification of waste sorting procedures is necessary to rally public sentiment. This advertisement would primarily come from the support of local political leaders. It is expected that these politicians would view the support of a commercial pyrolysis unit as an advantageous political move, due to the environmental and economic benefits this process would provide for NWA. These political leaders would use their platform to promote the plan for a commercial pyrolysis unit and its benefits to the general public in order to increase community involvement in the recycling of plastic waste. This support would consist of media advertisements, as well as implementation of policies and legislation that are favorable for the success of the pyrolysis plant. Political influence is also necessary to convince all municipalities in the area to cooperate in the delivery of their plastic waste streams to the central materials recovery facility. This political advertisement model is effective because the community will most likely respond well to leaders that they trust and are familiar with.

For the commercial pyrolysis unit to receive a mixed plastic feed, the central materials recovery facility must also choose to cooperate with the process proposed by Pyrolypigs. The facility would likely experience an increase in plastic waste throughput as a result of the proposed advertising campaigns. This center would also have to adopt new procedures for the processing of plastics. A stream of non-bottled # 1 and #2 plastics, along with plastics #4- 6, would be sorted and baled. The bales would be shipped to the pyrolysis unit using contracted tractor trailers. The materials recovery center will incur costs from the purchasing of balers and the increase in sorting demand. These costs are accounted for in the purchase price of the mixed plastic feed by the commercial pyrolysis unit. Therefore, motivating factors for the materials recovery facility to cooperate with the commercial pyrolysis plan would include profit through financial compensation as well as an expanded market for plastic waste. Ideally, the plastic feed to the materials recovery facility would increase due to increased consumer participation and the addition of participating municipalities. These beneficial factors that come from cooperation with the pyrolysis unit would be advertised to the materials recovery facility through political networking and scheduled business meetings.

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XI. Audits

Audit #1- Economics:

Auditor: Matt Berner

Title: Landfill Supervisor

Company: Eco-Vista Landfill

Contact: mberner@wm.com

Comments:

There are a few areas that I would question. 31% return seems pretty high. I didn't see where large scale development plans or engineering plans were included in cost of constructing location.

The facility will be required to have permit expenses from ADEQ, Air Permit, NPDES (water permit). ADEQ also requires leachate management for disposal facilities. There is an added expense for disposal at WWTP's. Existing permitted landfill space is incorrect. Current permits amount to about 62 years. In most areas, solid waste districts will not permit beyond 30 years. You will also have a disposal fee for the residue. MSW's cannot take this residue waste. Those wastes have to go to a hazardous waste facility. Purchase price of $75 per bale is low. It costs $49 to $52 to produce 1 bale of plastic. The bales will typically weigh around 1300 lbs. This allows 33 bales on an 18 wheeler, or $2475 for a load. #1 & #2 bottles are currently trading between $.0991 to $.1065 per lb, or $4686 per load. This would mean you would have to pay $142 per bale to purchase plastic. 2 years ago, it was trading around $.35 per lb.

On equipment expense, I didn't see how you were going to load/unload trailers and move product within the facility. At a minimum, you would need 2 forklifts ($5000 per month each for rental) and a wheel loader to feed hopper (100 hp wheel loader minimum rental $3750 per month). I also don't see maintenance expenses accounted for machine maintenance.

I would figure in another 12% for maintenance fund per year. This allows for breakdown repairs and monthly maintenance. With Bentonville & Bella Vista, they are under contract with an out of state company and their msw goes to Lamar, MO. They are currently selling their single stream material to a local mrf.

Audit #2 Legal Issues:

Auditor: Kyla Kaplan

Title: J.D. Graduate and Graduate Law (LL.M.) Candidate

Company: University of Arkansas

Email: kkaplan@uark.edu

Comments:

I do not see very many legal issues with your paper. There generally are not many legal areas that you address in your paper as long as your information is accurate, and you fully disclose your policies and procedures. My biggest concern would just be to make sure that your citation format is consistent and follows the requirements for your field.

Make sure you cite everything – it is always better to over-cite rather than under-cite because you never want to take credit for work that is not yours. This includes on photos and tables as well. Otherwise, as long as you are fully disclosing your information and providing credit for work you did not conduct, I think it looks good.

The biggest legal issue I could see here is not giving credit to the sources you used in your experiment and the people who helped you. It is also important that the citation format is consistent.

Audit #3- Health Issues:

Main auditor: Andrea Hopkins, Senior Policy Advisor (hopkins@adeq.state.ar.us)

Other parties: Alex Kreps, Office of Land Resources (kreps@adeq.state.ar.us)

Jesse Smith and Chris Riley, office of Air Quality (smithjf@adeq.state.ar.us)

Jessica Sears, Office of Water Quality (Jessica.Sears@adeq.state.ar.us)

Lucy Cross: Hazardous Waste (cross@adeq.state.ar.us)

Company: Arkansas Department of Environmental Quality (ADEQ)

NOTE: Audit was performed verbally through a zoom call. The following is a transcription:

Andrea Hopkins: <general introductions>

Air Quality- Chris Riley:

Your process is going to need a lot of permitting; General permits have overarching things. Most permits are specialized where they go through specific federal regulations and write out actual details in a permit. On average, you're looking at 5-6 months for a permit process across all of air. This would include the time necessary for submitting the application, a technical review by a board of engineers, a draft review and opening up for public comments. From the looks of it, a few permits will apply.

First, if you are over a certain amount of emissions, you will have a minor permit. For federal subparts, you have to have a permit no matter what amount of emissions, and it looks like you have a few of these in your stream. You can find a list in this resource:

https://www.ecfr.gov/cgi-bin/text-idx?SID=bbefda826db646549e631c88add52282&mc=true&tpl=/ecfrbrowse/Title40/40tab_02.tpl

We also have some links for the permits needed for things like equipment links and reactor processes in sections 3VA and 3

https://www.ecfr.gov/cgi-bin/text-idx?SID=db548bf97b9c4e2d7af646727ac0ed67&mc=true&node=sp40.7.60.vv_0a&rgn=div6#se40.7.60_1481a

https://www.ecfr.gov/cgi-bin/text-idx?SID=db548bf97b9c4e2d7af646727ac0ed67&mc=true&node=sp40.8.60.rrr&rgn=div6#se40.8.60_1707

You will want to look at Title 40: Environmental Protections in Part 60- volumes 7 and 8.

Then, volatile organic liquids in tanks have regulations, too. Subpart KB comes into effect when storage tanks are above the size of 75 m^3. Your tanks right now are at 105 m^3, so you may consider reducing the size of the load to avoid those permits.

There are three levels of Permits: Registrations, Minor Source and Title V. Title V is the level where big, nasty regulations come into play and you must stay inside that range.

ADEQ Permits are actually two permits rolled into 1. The first permit is necessary before you even begin construction. Arkansas does all of the permitting at once, so you would need to have a full permit before you could do anything. At the time of the permit application, you'd have a site picked out and a design to show an engineering company.

Air Quality- Jesse Smith:

As for the flaring, we only care about the fact that flares are there, they're on and functioning when needed, and what emissions they are producing. As long as you know how many BTU's of natural gas are burned per hour based on conservative calculations, the permitting is not that difficult.

Solid Waste: Alex Kreps

Because your facility will be considered an MRF, it will be exempt from permitting for waste. If the char is nonhazardous waste, it can just go in the trash.

I recommend that you also compare this process to other current recycling technologies out there reducing recycling in the MSW stream. Get the economics on those and the environmental impacts to compare.

Hazardous Waste: Lucy Cross

Because it's hard to predict what will be in the char, you'll want to do a waste determination test on the waste being produced. If you're selling it, that's a different case. When you start to get into haz waste, things get really tricky really fast.

Water Waste: Jessica Sears

Water waste isn't very complicated for permitting, since you're sending to a water treatment facility. However, for what municipality is accepting your wastewater, you will have to determine what their requirements are. However, their would be permits for stormwater. Any facility that constructs or disturbs more than 1 acre, will have to get a stormwater permit. It's easier if the land coverage is between 1-5 acres. You have to have a paper to keep onsite, but don't have to turn anything in. When doing construction and you get stormwater, you'll be concerned with pollutants washed off during construction, but that's only required during construction.
A likely permit that will last is the industrial stormwater general permit, which is really easy to get. That's if you are concerned about anything getting washed off during operation. You can get a no-exposure exclusion if everything is inside, but you will still have to get the permit. Both are on the website and only take a few weeks to get: https://www.adeq.state.ar.us/water/permits/npdes/stormwater/

The first two tables are for construction stormwater. The next two tables are for industrial stormwater. Don't worry about the rest of the tables.

You do have to have general permits for cooling towers and water blowdown, etc. if you choose to use that equipment. They have general permits for that too.

https://www.adeq.state.ar.us/water/permits/npdes/nonstormwater/

Most of these probably won't apply but some would.