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Pyrolysis of Non-Recyclable Plastic Waste to Energy and Carbon Nanotubes

[1]Abdalhameed Abdalahmeed Alsayyid, [2] Asmaa Alhassan

[1] (aka A. H. Harb), Dept. of Business, French University of Egypt, Sherouq City, Cairo Egypt
[2] Dept. of Business, French University of Egypt, Sherouq City, Cairo Egypt

Email: abalhameed.harb@gmail.com, asmaa_alsharif@yahoo.com

Abstract: *On average, more than 50% of the plastic used around the world can be classified as single-use. Each minute, an average of one million plastic bottles are purchased around the world. As such, plastic waste has developed into one of the leading environmental problems. The objective of the study is to explore the process of converting non-recyclable plastic waste to energy and carbon nanotubes (CNTs). It investigates the processes like gasification and catalytic pyrolysis to convert the nonrecyclable plastics into high-value products like energy (electricity and carbon nanotubes). The systematic review narrows the volume of studies incorporated*

from 72 to 5 for a higher quality research. The studies reviewed and integrated show that there are different yields and quality based on the type of plastic waste feedstock. Industrial pyrolysis is an integral process in the conversion of the nonrecyclable plastic waste into energy and CNTs. The industrial pyrolysis process is fundamental in the conversion of nonrecyclable plastic waste into energy and CNTs. The process is key especially given the dismal recycling rates and the rising environmental challenge.

Key Words: *Carbon Nanotubes, Non-Recyclable plastics Gasification, Industrial pyrolysis, Thermoset plastics, Thermoplastics, Microplastics, and Monomers & Polymers.*

1. INTRODUCTION :

According to He et al. (2021), plastics have grown into fundamental materials integral to everyday life. Although plastics have numerous uses, they have brought about one of the biggest environmental challenges of the modern times Data collected from the UNEP (United Nation Environmental Programme shows that people have become accustomed to the use of disposable/single-use plastics (UNEP, n.d.). For example, on average an estimated 50 percent of the plastic produced in the world is meant to be used once. Current estimates show that each minute an average of one million plastic bottled are purchased (He et al., 2021). Data collected from the EPA (Environmental Protection Agency shows that as of 2018 the bulk of plastic waste totaled 14.5 million tons and emanated from the containers and packaging category ("Plastics: Material-Specific Data | US EPA", 2019). Plastic waste has developed into one of the biggest environmental challenges of the 21st century. It is worth noting that despite efforts to recycle the plastic waste, organizations and agencies have only managed to recycle a small percentage. For example, the EPA estimates show that in 2018, the USA only managed to recycle 8.7% of the plastic waste. The highest plastic recycling rate was 29.3% for HDPE (high-density polyethylene) natural bottles and 29.1% for PET (polyethylene terephthalate) bottles and jars ("Plastics: Material-Specific Data | US EPA", 2019).

Numerous studies have shown that waste management has become a major challenge. For example, in a recently concluded study, Alabi et al. (2019) have established that in the past decade, there has been an average of three hundred million tons of plastic waste produced. Of this waste, only an estimated 15% is recycled. An estimated 90 million tons are mismanaged and become environmental pollutants (Ragossnig & Agamuthu, 2021). Plastic pollution has a huge impact on aquatic ecosystems as an estimated 13 million tons of plastic waste find their way into the oceans resulting in the loss of tens of thousands of aquatic lives (Alabi et al., 2019). Another challenge found in plastic waste concerns the non-recyclable feedstock. Research shows that mixed plastics and composite plastic products cannot be recycled mechanically unless properly separated (White et al., 2021).

Since the global demand for plastics is on the rise, and the recycling rate is dismal, there is a need to develop better forms of plastic waste management. Researchers have developed thermochemical recycling processes such as catalytic pyrolysis and gasification where plastics are used to create higher value products like carbon nanotubes, energy, fuel oils, and gasoline among others (Hedayati et al., 2019). The current plastic recycling process is dominated by mechanical recycling which is highly inefficient. A better alternative is found in the thermochemical recycling processes due to the creation of high-value usable end products. This study will explore catalytic pyrolysis and gasification as processes and technologies used to convert the non-recyclable feedstock to high-value end products like carbon nanotubes and electricity.

2. BACKGROUND :

Plastic waste management is a growing environmental concern across the world. According to Zhang et al. (2021), researchers have estimated that the global volume of plastic will double within the next two decades. The vast unmanaged plastic waste leaks into the environment creating nano-plastics that affect both aquatic and terrestrial ecosystems. The micro and nano-plastics can be ingested by different organisms and accumulate in plants. They can then serve as a medium for the spread of different pollutants, diseases, and heavy metals. Recent studies have shown that microplastics have entered people's food systems thereby threating food safety (Hou et al., 2021). The improper management of plastic waste results in both environmental pollution and a loss of economic value. For example, plastic recycling is associated with energy savings of up to $176 billion (the equivalent of 3.5 billion oil barrels) (Hou et al., 2021).

Mechanical recycling is typically used to convert the HDPE and PET into new low-grade plastics. Another process used to manage plastic waste is the energy recovery process through incineration. The process results in the burning of huge volumes of plastic to generate heat and other forms of energy (Williams, 2021). However, the process also results in the creation of harmful gases such as mercury, furans, dioxins, and BCPs (polychlorinated biphenyls). It also releases a lot of soot that affects air pollution. While a lot of plastic can be disposed through this process, the disadvantages outweigh the benefits. When disposing of plastic waste through incineration, they can be classified as either thermoplastics or thermoset plastics. The thermoset plastics (hard plastics) are usually difficult to recycle as they cannot be melted and reused unlike the thermoplastics. Additionally, the two approaches (mechanical recycling and incineration) do no provide adequate solutions to the challenge of plastic waste management. Some of the shortcomings associated with traditional recycling approaches include the high costs, low benefits, and secondary pollution (Hou et al., 2021). It necessitates the development of cost-effective, efficient, and environmentally friendly recycling strategies.

Researchers have proposed that a better solution for plastic waste management is developing strategies to reuse plastics on a larger scale. Various solutions have been developed surrounding the use of effective catalytic degradation technologies to create high-value materials, fuels, and chemicals. It is worth noting that there is a vast new economy surrounding new recycling technologies to develop high-value usable products. According to Hou et al. (2021), recycling through thermochemical routes entails processes such as pyrolysis, depolymerization, and gasification. Pyrolysis (also known as liquefaction or thermolysis) is the process of converting the plastic feedstock to wax, gases, or liquids under extremely high temperatures (Williams, 2021). The process can be conducted in the presence or absence of a catalyst. Gasification entails the production of gas products through the use of high temperatures and gasification agents like oxygen.

According to Yao et al. (2020), the commercialization of plastic waste management to leverage the high value products would promote the rate of plastic waste collection and recycling. For instance, one of the notable products is the CNT (Carbon Nanotubes). CNTs have been shown to have multiple uses in technology such as energy storage, creation of biosensors, electronic components, and reinforced composites for airplanes (Wu et al., 2012). CNTs are traditionally created through a chemical vapor deposition process using carbon-rich gases. When creating CNTs from the plastic waste feedstock, the plastics are exposed to high temperatures (for thermal degradation) to create the different hydrocarbon volatilities that are used as to provide the carbon-rich precursor (Yao et al., 2020). The precursor then proceeds to the next stage where there are catalysts to produce carbon vapor deposition at high temperatures (average of 800^{o}C). Scholars contend that the yield and quality of the carbon nanomaterial is dependent on the feedstock, reactor type, catalyst, steam, feed rate, and temperature. Different catalytic metals are used in the process such as Ni (Nickel), Co (Cobalt), and Fe (Iron).

According to Yao et al. (2020), Nickel is among the most used active metals for catalytic plastic waste conversion. The benefit of using Nickel is its high ability to break the carbon-carbon bonds and the carbon-hydrogen bonds. The most cost-effective active metal to use on the conversion process is iron due to its availability and low-cost. Researchers have found that bimetallic catalysts can have higher activity towards the carbon nanomaterials resulting in increased yields (Yao et al., 2020). A recent study has shown that the use of Fe-Ni/Al2O3 bimetallic catalysts for the catalytic carbon vapor deposition of ethylene resulted in a three times higher yield than when using an Fe-based catalyst (Ratkovic et al., 2011). The use of bimetallic catalysts has been shown as more stable catalysts for the creation of carbon nanotubes from methane.

Fuel Generation

According to Fahim et al. (2021), the plastic waste feedstock can be converted into usable fuel. First, the feedstock is shredded and mixed in with the catalysts in the reactor (for catalytic pyrolysis). The feedstock is then heated to 550oC at a stable rate of 15oC per minute. The pyrolysis process then creates oil and gas vapor as the products. The next stage involves the condensation of the vapors to produce fuel oil, heavy oil, and the light hydrocarbon gas (Fahim et al., 2021). The hydrocarbon gas is stored and used for combustion thereby making the pyrolysis process sustainable. The fuel oil is supplied to the refineries to be converted into gasoline and diesel. The heavy oil is also sold for use in the commercial shipping industry. The fuel produced in the plastic waste conversion process has a calorific value of 9829.3515 kcal/kg (nearing that of diesel) (Fahim et al., 2021).

3. STUDY OBJECTIVES :

The paper aims to discuss and analyze the technology and processes used to convert the non-recyclable plastic feedstock to generate electricity, CNTs, and fuels.

4. MATERIALS AND METHODS :

The nature of the research paper is to provide exploratory research on the thermochemical processes of managing plastic waste. The study will follow the design of a systematic literature review. There is vast research on the topic of plastic waste management and the processes of pyrolysis and gasification. The articles conducted can then be vetted and analyzed to help provide relevant information to support the study's objective.

5. LITERATURE REVIEW :

5.1 Plastics

Plastics are semi-synthetic organic compounds created from fossil fuels. However, not all plastics are created from fossil fuels; others are developed from biomass sources. Most of the plastics produced around the world are obtained from petrochemicals. Statistics show that an estimated 4% of the global petroleum production is used as a petrochemical feedstock for plastics (Hopewell et al., 2009). The high use of plastics has been due to their numerous features. For instance, they are lightweight, durable, resistant to corrosion, easily malleable, and relatively inexpensive to produce (Alhazmi et al., 2021). Other features associated with plastics are that users can add additives to determine their elasticity, thickness, opacity, and thermal properties.

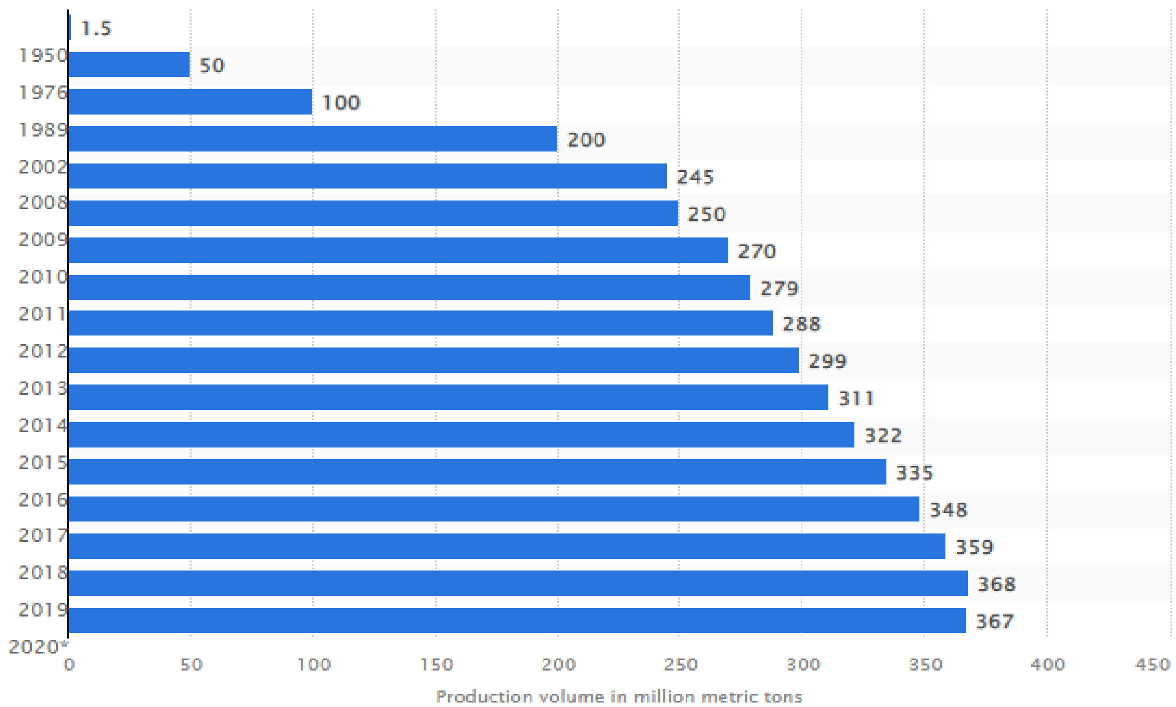

Figure 1: Annual global plastic production from 1950 to 2020 (Tiseo, 2022)

The most common types of plastics are categorized as either thermoset plastics or thermoplastics (Alhazmi et al., 2021). The primary difference between the two is that thermoset plastics often harden when exposed to heat while thermoplastics soften. Examples of thermoset plastics include electric plugs and electric kettles. Examples of thermoplastics include single-use bottles and PVC pipes. There is a higher volume of thermoplastics compared to thermoset plastics. The annual plastic production has continued to grow at an exponential rate (see the figure below).

In the production of plastics, there are microplastics (these are small polymer pieces <=5mm in size) that can be challenging to recycle. Some of the reasons for this include the challenge in collecting and reusing plastics (Alhazmi et al., 2021). When plastic waste disposal takes place in landfills, it can take an estimated 500-1000 years to degrade (Uekert et al., 2019). Therefore, disposing of them in landfills is not a sustainable or viable alternative.

Before exploring how plastic is recycled, it is necessary to review the lifecycle of plastic products. Their lifecycle begins through the extraction process, where the petrochemical feedstock is used to create plastics (Alhazmi et al., 2021). The second step entails the preparation of the monomers and their assembly and consequent production. Step three in the lifecycle is the fabrication of the plastic into different materials such as plastic packaging, tires, pipes and many others. The fourth step is the use of plastics. For example, plastic water bottles can be used for water. After use and depending on the quality of the plastic, it reaches the end-of-life stage. Here, the plastic is disposed of in the garbage or other areas. The plastic waste can then either be taken to a recycling facility or deposited in landfills. The figure below explores the lifecycle of plastic products.

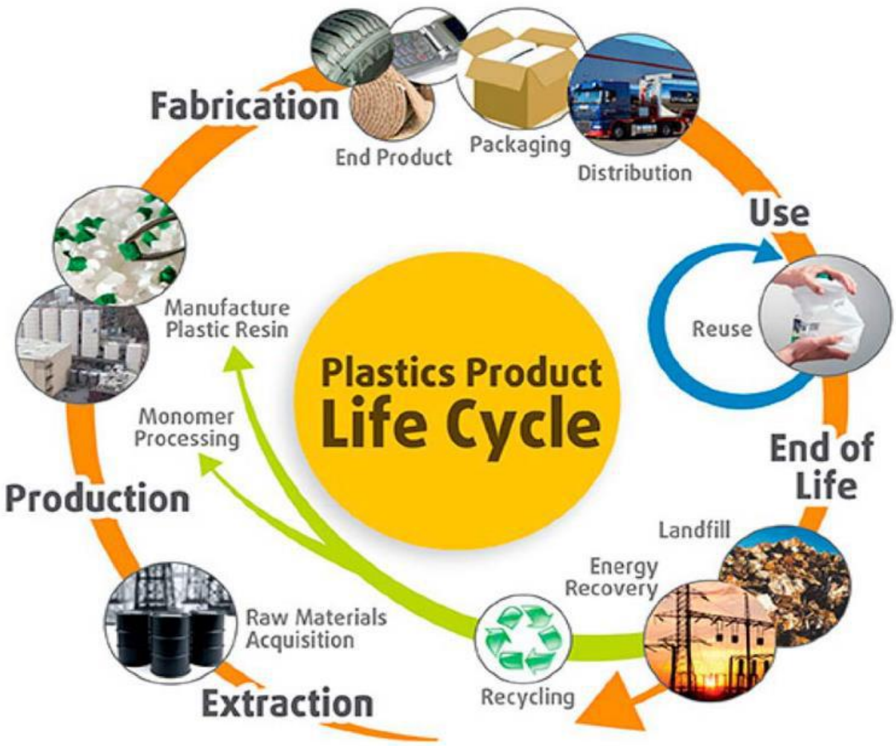

Figure 2: Lifecycle of plastic products (Alhazmi et al., 2021)

Chemists classify plastics as polymers meaning that they are produced from multiple threads of monomers (Uekert et al., 2019). As such, the polymers have much larger molecules. Since the bulk of plastic is produced from synthetic materials, they comprise elements such as hydrogen, sulfur, chlorine, nitrogen, carbon, and oxygen (Alhazmi et al., 2021). The production of plastics entails the use of polymeric tar mixed in with added substances. Chemists typically use different substances to manufacture plastics with desired qualities for defined purposes.

5.2 Plastics Waste Management

Research shows that a huge volume of the plastic produced is used to make disposable items and short-lived products such as single-use bottles (Hou et al., 2021). These plastics are discarded within the same year of production. It shows that the current system of plastic use is highly unsustainable. The production of plastic is highly advanced, and many of the polymers created are highly durable. Due to the relatively low level of plastic recycling, these durable plastics are either disposed of in landfills or out in the open (Wu et al., 2016). Improper plastic disposal results in their integration into natural ecosystems, thereby affecting flora and fauna. According to Uukert et al. (2019), estimates indicate that an estimated $176 billion (3.5 million oil barrels) can be saved annually if plastic waste recycling reaches 100%.

According to Ragossnig and Agamuthu (2021), each year, an estimated three hundred million (300 million) tons of plastic resin are produced annually. The bulk of it ends up as waste (218 million tons). Current estimates show that the global plastic recycling rate is estimated at a dismal 15% (Ragossnig & Agamuthu, 2021). Europe is one of the areas where recycling has taken root, as reports show that in 2018, they managed to recycle 32.5% of the 29.1 million tons of plastic waste collected (Yao et al., 2019). A considerable volume of plastic waste is mismanaged each year (more than 90 million tons). As an example of the 14 million tons of plastic waste produced in China, more than 75% was mismanaged (Jambeck et al., 2015).

According to Hou et al. (2021), there are four primary categories of plastic waste, polystyrene, polyester, polyvinyl chloride (PVC), and polyolefin. One of the most used polyesters is PET (polyethylene terephthalate). It has a global production volume exceeding 70 million tons and is used in single-use bottles, carpets, textiles, and packaging (Hou et al., 2021). Polyolefins such as polypropylene and polyethylene account for an estimated 57% of the municipal solid waste with an annual production of 138 million tons. PVC is the cheapest plastic, and it is classified as the leading problematic plastic waste. It is because, during its end-of-life treatment, it emits dioxins (hydrocarbons containing chlorine) and phthalate plasticizers (Hou et al., 2021).

5.3 Plastic Recycling

Recycling has been a topic of concern since scientists and scholars determined that humans were living unsustainably by causing significant damage to the environment. Despite the low levels of plastic recycling, it is among the best options for plastic waste management. The 6R principles of plastic waste management emphasize reduction, repair, reuse, recover, remanufacturing and recycling (Hou et al., 2021). Plastic recycling has been categorized into primary (closed-loop), secondary (mechanical), and tertiary (chemical) recycling. Primary recycling is where the discarded plastic is used to make new items and products that serve a similar function. Secondary recycling is where the plastic waste is exposed to mechanical recycling to create new products whose functionality is different from that of the initial process. For example, the plastic feedstock is exposed to mechanical force and high temperatures to degrade the plastic polymers. The shortcoming of mechanical recycling is the emission of volatile and harmful organic compounds (Hou et al., 2021). Tertiary recycling is where the plastics are recycled using chemical processes such as depolymerization, pyrolysis, and gasification.

5.4 CNTs

CNTs have multiple applications across the world. Due to these utilities, the CNT market size was calculated as $4.9 billion. The industry projections expect the CNT market size to grow from $5.32 billion in 2021 and eclipse 10.52 billion by 2028 ("Carbon Nanotubes (CNT) Market Size", 2021). Engineers from MIT have developed multiple advancements on using CNTs from their use in developing microprocessors. Another fast-rising application of CNTs is in the aerospace industry as they are used to craft the fuselage and enhance the aircraft’s performance. The figure below shows the global CNT market share by application in 2020.

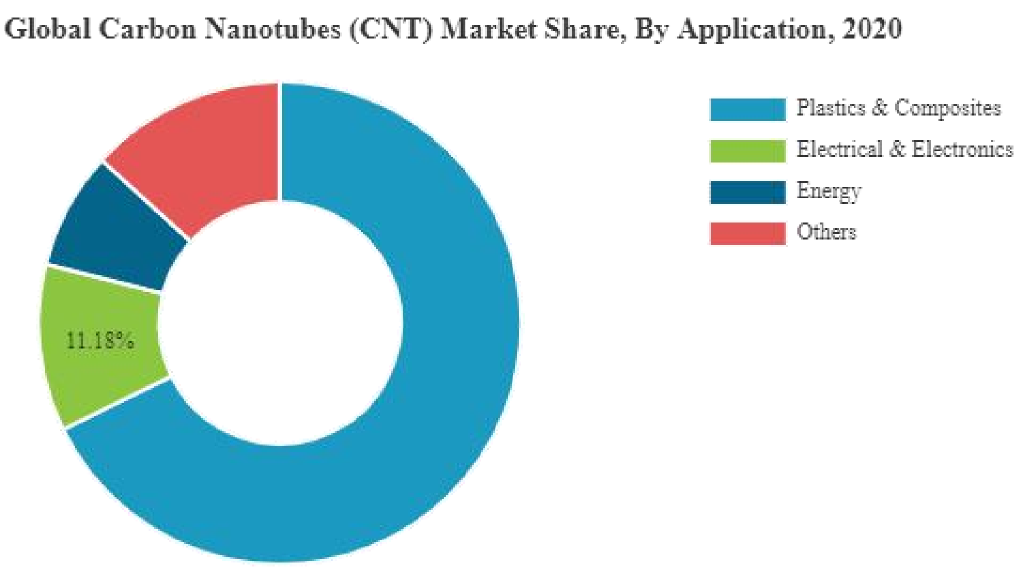

Figure 3: Global CNT market share by application ("Carbon Nanotubes (CNT) Market Size", 2021)

5.5 Industrial Pyrolysis

According to Hou et al. (2021), pyrolysis is the process where high temperatures and catalysts are used to convert plastic feedstock to waxes, liquids, and gases. A study conducted by Yao et al. (2020) explored the pyrolysis-catalysis of waste plastic feedstock using different Ni-Fe catalysts and a two-stage fixed bed reactor. A similar study was conducted by Wu et al. (2016). The schematic diagram below shows the pyrolysis reaction system.

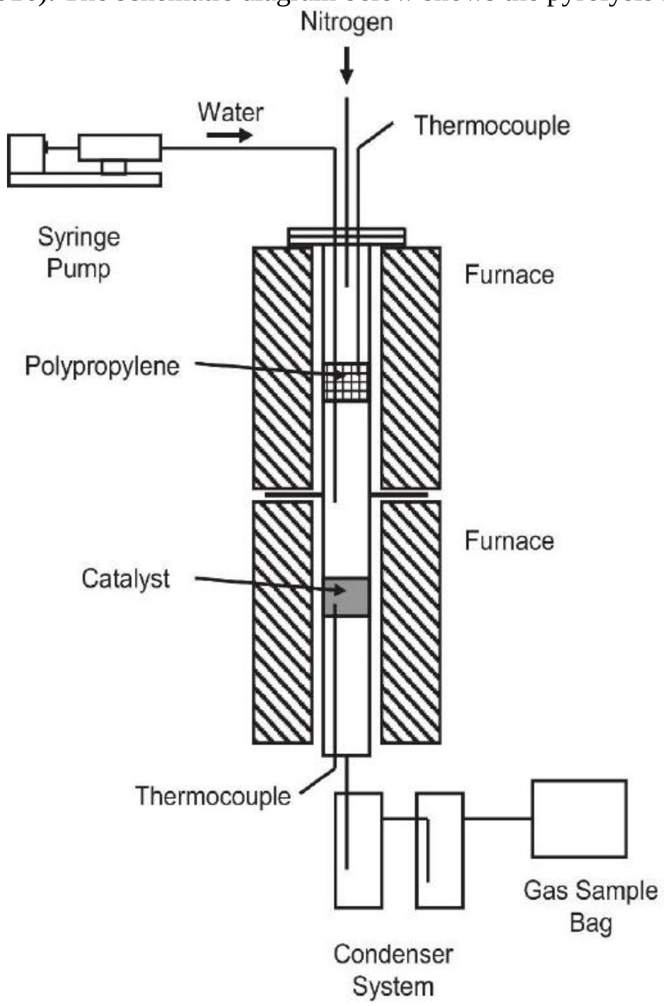

Figure 4: Diagram of the reaction system

5.6 Synthesis of Liquid Fuel

According to Fahim et al. (2021), different types of plastic waste can be converted into fuel. In the conversion process, the plastic waste feedstock is cleaned, dried, and cut into small pieces. The fast pyrolysis process is then used to convert the waste into fuel. The small pieces are required to be (1x3cm2) so that they can fit within the reactor. In the conversion of plastic waste into fuel, an appropriate catalyst is required. Fahim et al. (2021) contend that the use of the Zeolite Socony Mobil-5 (ZSM-5) is appropriate. ZSM-5 has an extensive history of use within the petroleum industry as a heterogeneous catalyst for hydrocarbon isomerization reactions. While preparing the catalyst, it needs to be dried in the oven and achieve a moisture level of less than 5%, then broken into smaller pieces (Kumar et al., 2018). In the reactor, the plastic to catalyst ratio is given as 10:1 (Kumar et al., 2018). One of the benefits associated with the use of the catalyst is that it reduces both the temperature and time needed for the reaction. As such, the conversion rates of numerous polymers are enhanced.

The Process

First, the plastic feedstock is cleaned and dried to remove any toxins that could affect the quality of the desired end-product (the fuel). The clean feedstock is then shredded and mixed in with the ZSM-5 catalyst (in the ratio of 10:1) (Kumar et al., 2018). Different types of plastic waste have varying quantities and ratios. The figure below shows how the pyrolysis process works.

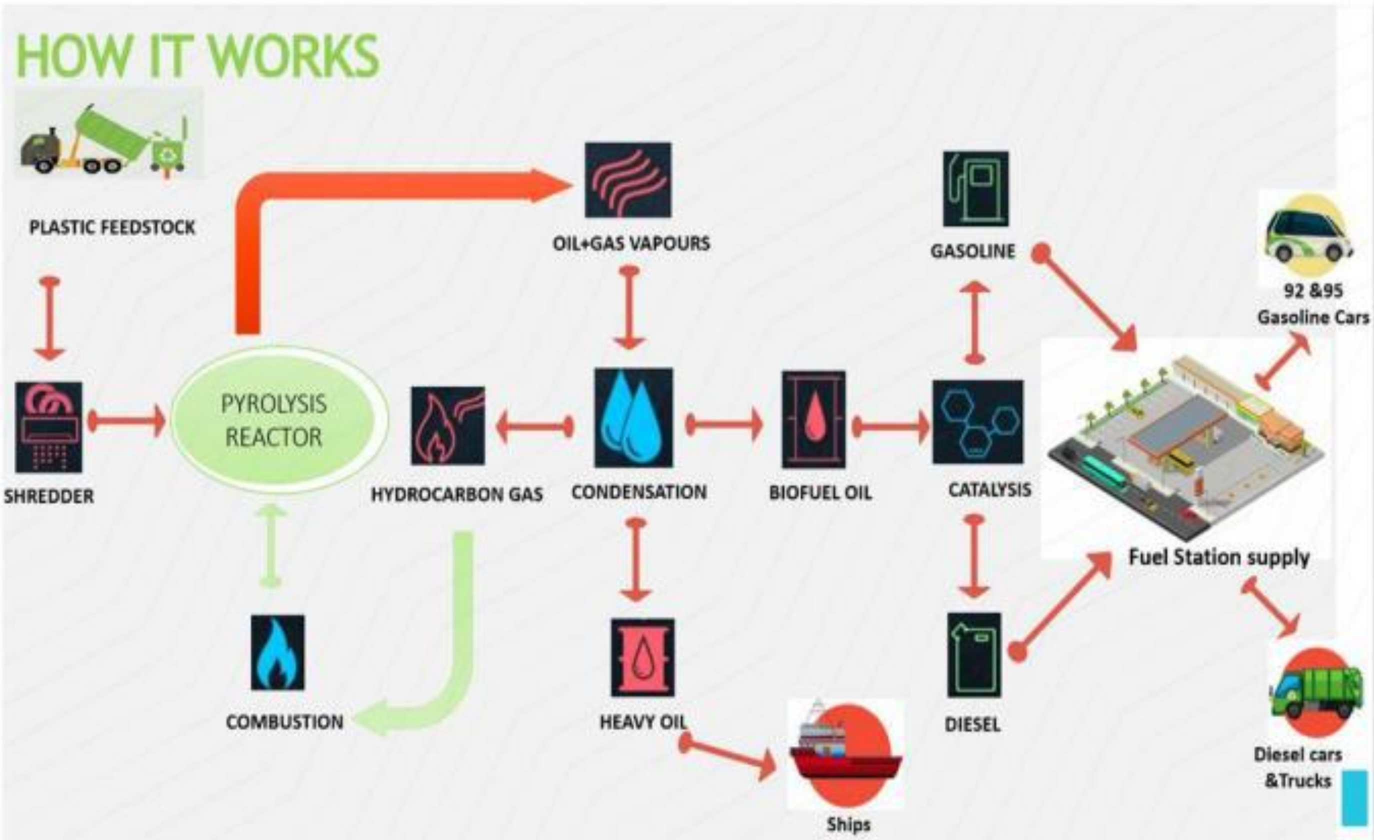

Figure 5: The pyrolysis process

The pyrolysis reactor used is mainly a flatbed. Within this reactor, the plastic and catalyst mixture is heated at a steady rate of 15ºC/minute to reach the maximum temperature of 550ºC. As a result, oil and gas vapor is produced. The byproducts then undergo condensation to produce the different types of gas and fuels (heavy oil, fuel oil, and light hydrocarbon gas) (Fahim et al., 2021). It is interesting to note that the energy in the pyrolysis system is self-sustaining as the hydrocarbons produced are stored and reused in the combustion. The different end-products have multiple applications. For example, the biofuel oil is combined with the ZSM-5 catalyst and converted into gasoline and diesel. The gasoline is then used to create electricity. Commercial ships are provided with heavy oil. One of the primary issues of concern here is the quality of the oil (which is determined through its calorific value). Measuring the calorific value of the oil entails an assessment of the energy produced when its unit mass is combusted in enough air. Studies used the IP 12/58 method to determine the calorific value of the biofuel oil as 9829.3515 kcal/kg (Fahim et al., 2021). It is close to that of diesel (11000 kcal/kg).

5.7 Production of Carbon Nanotubes (CNTs) from Plastic Waste

According to Williams (2021), CNTs are hollow cylindrical tubes created using carbon and with nano-sized diameters. Depending on their functionality, the CNTs can either be single or multi-walled. CNTs have attracted special attention among manufacturers due to their characteristics. For example, CNTs are both physically and chemically stable, have a high tensile strength (exceeding 100 times that of stainless steel), and have high electrical conductivity (Williams, 2021). As such, these CNTs have numerous applications, from the creation of tires, solar panels, conductive coatings and paintings, microelectronics and semiconductors, and other devices.

There are numerous processes used to produce the CNTs from CVD (chemical vapor deposition), laser ablation, and arc discharge production. The process of laser ablation entails the use of extreme temperatures (1200oC) for carbon vaporization. Arch discharge production entails the exchange of electrical arc discharge between carbon electrodes, thereby resulting in the production of CNTs on the negative electrode (Williams, 2021). The pyrolysis process of producing CNTs results in the production of polymer fragments and aliphatic and aromatic hydrocarbon gases due to the use of mixed plastics.

Scholars contend that the production of CNTs from plastic waste is largely based on the two-stage pyrolysis-catalyst reactor (Williams, 2021). Before the development of the two-stage reactor, the single-stage was used. In this reactor, the plastic waste is combined with the catalyst in the same reactor and the separate pyrolysis steps are performed on the same reactor. An excellent example of the single-stage reactor can be seen through the works of Kong and Zhang (2007). The scholars used an autoclave reactor to produce CNTs. In their experiment, the autoclave reactor (with the polyethylene waste feedstock) was sustained at 700ºC for 12 hours and the process yield comprised of more than 80% CNTs of between 20nm and 60nm diameter (Kong & Zhang, 2007).

Since then, there have been numerous developments. For instance, there is the two-stage pyrolysis-catalyst reactor design. The benefit of this design is that there is enhanced control over the entire process, from the pyrolysis phase to the chemical vapor deposition phase (Williams, 2021). These reactors are also known to produce higher volumes of CNTs. A study by Acomb et al. (2015) used the two-stage fixed bed reactor system. The two stages were conducted on separate and independent reactors. Through this approach, the scholars managed to control the conditions on both the pyrolysis and catalytic reactors (Acomb et al., 2015). In the study, the plastic waste feedstock comprised of low-density polyethylene and a Fe-Al2O3 catalyst. Acomb et al. (2015) established that raising the catalyst temperature to 900oC resulted in higher CNT yield. However, at the higher temperature, less structured CNTs were produced compared to the lower temperature of 700oC.

Studies show that the most common metals used as catalysts in the production of CNTs are Fe, Co, and Ni (Wu et al., 2012). The two primary reasons for their preference are that carbon diffusion can achieve the highest rates in metals, and carbon solubility can also reach high levels at high temperatures (Wu et al., 2012). Organometallocenes are also used as catalysts in place of metal-based catalysts. These organometallocenes have a unique property as their metal particles can be freed while in situ resulting in the decomposition of hydrocarbons to yield CNTs (Wu et al., 2012). When producing CNTs using the CVD process, some common catalysts used include silicon carbide, zeolite (alumina-silicate), graphite, quartz, and magnesium oxide, among others.

According to Williams (2021), the quality and yield (quantity) of CNTs produced are mainly influenced by the type of plastic used and the catalyst. The presence of impurities in the plastic feedstock affects the quality and quantity of CNTs. For example, the presence of chlorine in PVC plastic feedstock poisons the metal catalysts, thereby affecting the quality and quantity of CNTs produced. Research also shows that adding steam to the second stage (the catalytic reactor) affects the yield and quality of CNTs. Specifically, the steam vapor injection acts as an oxidizing agent for the amorphous carbon, thereby reducing the deactivation of the catalyst. The process produces longer and purer CNTs (Hata et al., 2004).

Despite the implied benefits of the process, there are various issues to consider. For example, during the CVD process, the CNTs can be entangled with the catalyst's particles, thereby challenging their recovery (Zhang et al. 2017). Research also shows that when using the nickel impregnated stainless steel mesh in the catalyst stage, the production of CNTs was followed by the production of carbon nanofibers (solid fibers) (Zhang et al., 2017).

6. METHODOLOGY :

The structure of the study closely follows that of a systematic review. The purpose of the study is to explore the conversion of non-recyclable waste plastic into electricity and CNTs.

6.1 Selection Criteria

The first step of the research methodology process entails the collection of published studies that covered the conversion of non-recyclable plastic waste into electricity and CNTs. Therefore, the keywords "plastic waste conversion into electricity and carbon nanotubes," "creation of carbon nanotubes from plastic waste," and "plastic waste management," were used. The search was conducted across multiple databases such as Web of Science, Google Scholar, and JACS (Journal of the American Chemical Society). The search revealed a cumulative total of 434 articles. The second step entailed the screening of the papers to determine the most relevant and applicable to the current study.

The first elimination criteria were removing the studies conducted more than 10 years ago. It then reduced the volume of articles to 103. The second factor entailed the removal of duplicate papers, which reduced the viable studies to 72. Step three entailed the assessment of the remaining studies for their nature as only original studies (experiments) were desired. This step produced a smaller subset of 14 studies. The remaining 14 studies were then thoroughly assessed to determine the best studies for use in the project. This final step yielded 5 fundamental studies for use.

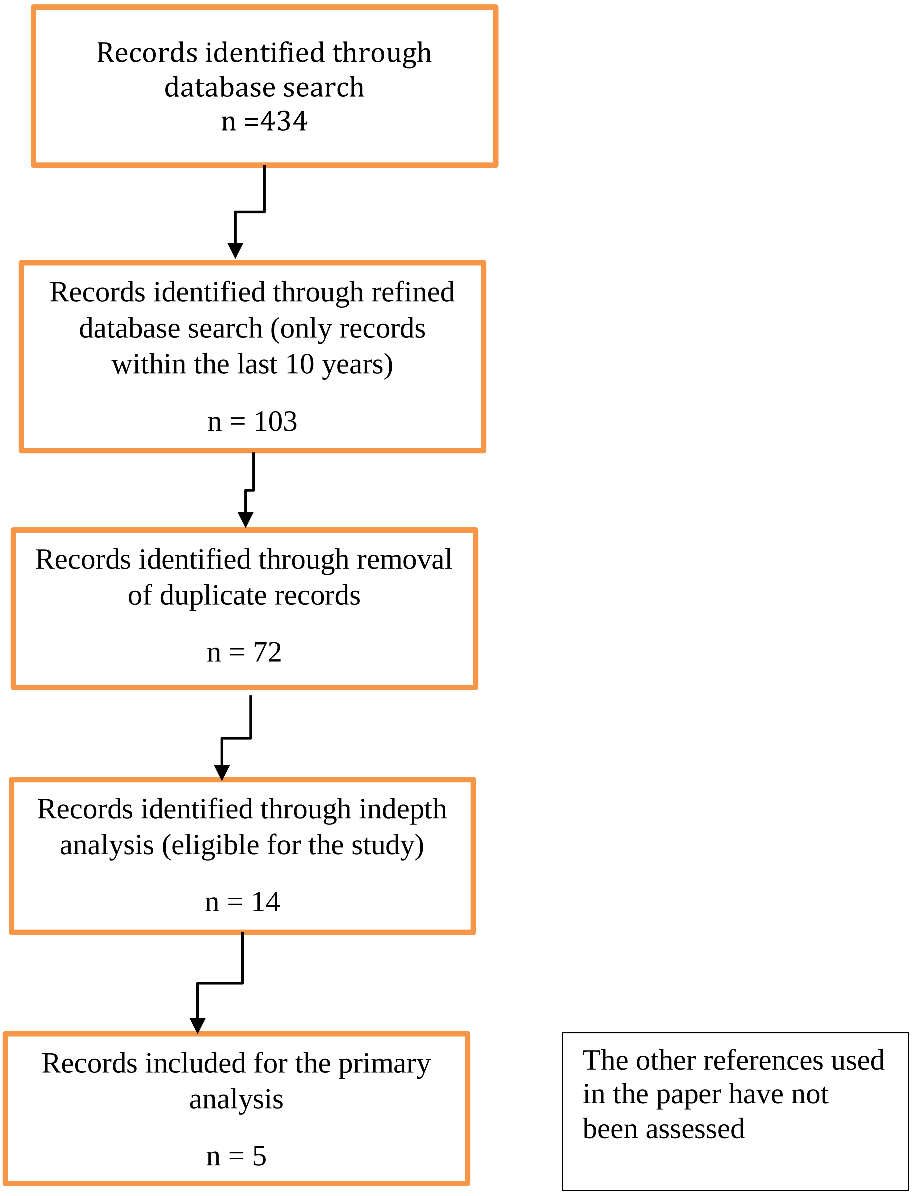

Figure 6: Research screening process

6.2 Data Collection and Analysis

Since the goal of the project is to describe the conversion of the non-recyclable plastic waste feedstock into electricity and CNTs, the studies used for review are assessed based on the quality of their content. The primary focus is on the processes used to synthesize the fuel and CNTs. The data collected from the experiment is explored and compared to the data from the other studies to provide a robust understanding of how non-recyclable plastic waste can be converted into useful products like fuel, energy, and CNTs.

6.3 Results and Discussion

In a study by Hedayati et al. (2019), the scholars grew MWCNTs (Multi-walled Carbon Nanotubes) through CCVD (Catalytic Chemical Vapor Deposition) in a two-zoned horizontal liquid injection reactor (LIR). The conditions for the growth of the CNT can be seen as: a temperature of 780oC and an injection of the 3-5ml of the solution at a steady speed of between 1-3mL/h with a consistent gas (it consists of 5% H2 in argon balance) flow of 1 L/min (Hedayati et al., 2019). In the project, the researchers used a 100-com long quartz tube measuring 38 mm in diameter. The catalyst used contained ferrocene mixed in with 5 wt.% toluene solvent. The experiment began with dissolving 16.5mg of plastic waste in the toluene solution before injecting the mixture into the LIR to produce the CNTs (Hedayati et al., 2019). The researchers ensured that the plastic waste was properly cleaned with soap and water before mixing with the catalyst.

The researchers found that the process was successful in producing CNTs. However, there were varying sizes of the CNTs produced (from 30 nm to 400 nm). The use of the polystyrene resulted in more uniform CNTs (not exceeding 120 nm in diameter). The polymer material helped to prevent the occurrence of Ostwald ripening or coursing (Hedayati et al., 2019). The experiment also validated the Puretzky model of CNT growth as an increased flow of carbon to the catalyst resulted in the formation of nanotubes with large diameters. The CNT presence was ascertained using the Raman spectroscopy (observing the fingerprint peaks D (1350cm-1), G (1570cm-1), and 2D (2700cm-1).

Another interesting experiment was conducted by White et al. (2021). The researchers sought to show that the upcycling of plastic waste into high-value products like CNTs is a viable alternative to manage the non-recyclable plastic waste. The experiment entailed the growth of MWCNTs through CCVD (Catalytic Chemical Vapor Deposition). It was conducted in a two-zoned horizontal liquid injection reactor (LIR). The control CNTs were grown similarly to those grown by Hedayati et al. (2019). The experiment also utilized a similar 100 cm long quartz tube with a 38 mm diameter (White et al., 2021). The plastic waste feedstock comprised of polystyrene, which was mixed in with the toluene concentrations of 1, 2, and 4 wt% w/w. The primary catalyst used in the reaction was ferrocene (5 wt% w/w) (White et al., 2021).

In the experiment, the scholars determined that the CNT grown varied in diameter ranging from 18 nm to 45 nm. The longest CNT strand identified measured 13.7 um. The scholars also used the scanning electron microscope to observe CNT structures as they are often tangled and have a long morphology (White et al., 2021). The MWCNTs fingerprint peaks were measured using Raman spectroscopy. High D peaks are associated with defects in the CNT structure. G peaks are used to indicate that the CNTs formed have multiple walls (they are MWCNTs).

6.4 Managerial and Organizational Implications

The studies reviewed to aid in exploring the growth/production of CNTs from non-recyclable plastic waste. The results show that the use of different types of plastic waste and catalysts leads to different types of yields and quality. The research also shows that the material needed to manufacture the CNTs is readily available. Given the ease and multiple applications of the CNTs, it is necessary to note that industrial pyrolysis is a viable alternative for the management of non-recyclable plastic waste. A study conducted by Hamid et al. (2021) found that the total production cost of a pyrolysis plant was $1.6 million annually. Given this rate, it stands to reason that the production of CNT from non-recyclable plastic waste is an economically viable endeavor. Consider that each year, an estimated $176 billion and above is wasted in fossil fuel for the creation of plastics. The management of municipal plastic waste should invest in the industrial pyrolysis process and acquire a few two-stage reactors to help in the upscaling of non-recyclable plastic. The government can benefit significantly from adopting this form of waste management as the end-products have a high value, and the proceeds can be used to enhance environmental management and sustain plastic waste management.

7. CONCLUSION :

The research conducted shows that plastic waste management is a considerable challenge, especially among those non-recyclable plastic waste. The current level of plastic waste recycling is at an alarmingly low rate (less than 25%) globally. It means that there is a necessity to seek out alternative strategies. The primary strategy explored is the conversion of plastic waste into fuel (which can then be used to produce energy) and CNTs. The primary process used is the industrial pyrolysis process. The experiments reviewed managed to create different types of CNTs. The quality of the CNTs created was affected by the quality of the plastic waste and the catalyst used. Although the process is extensive, it produces high-value end-products. For example, there is biofuel oil that is used for energy generation (has a calorific value close to that of diesel). The heavy oil can be used by commercial ships. Finally, the CNTs produced can be used for multiple other applications across industries such as aerospace, microchip manufacturing, tires, and automobiles.

8. Recommendation and Future Scope :

The main recommendations from the article point to the necessity of municipalities adopting the industrial pyrolysis process to convert plastic waste into high-value products. It is evident that setting up and sustaining the plant can be expensive. However, the end products produced are of high value, and they can help to cover the cost of the conversion while keeping the environment clean. Future studies should focus their efforts on studying different types of plastic waste and catalysts that help to produce high yield and high-quality CNTs. Such a focused study will assist in determining how to handle plastic waste.

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