# Method for Management and Reducing Plastic Waste

Subjects: Engineering, Chemical | Green & Sustainable Science & Technology | Environmental Sciences
Contributor: Farihahusnah Hussin

Plastic waste generation has increased dramatically every day. Indiscriminate disposal of plastic wastes can lead to several negative impacts on the environment, such as a significant increase in greenhouse gas emissions and water pollution. Products from the pyrolysis process encompassing of liquid, gas, and solid residues (char) can be turned into beneficial products, as the liquid product can be used as a commercial fuel and char can function as an excellent adsorbent. The char produced from plastic wastes could be modified to enhance carbon dioxide (CO2) adsorption performance.

Keywords: CO2 capture ; carbon emission and utilization ; adsorption ; plastic waste ; pyrolysis ; char

## 1. Introduction

The COVID-19 pandemic has had an unprecedented, harsh impact on the lives of people around the world. From another perspective, the pandemic has also changed the condition of the environment. For example, some parts of the world have seen improvements in air quality and a significant decrease in greenhouse gas emissions, which was hard to achieve before the COVID-19 pandemic. According to the International Energy Agency, the COVID-19 crisis in 2019–2020 has caused a significant drop in global carbon dioxide ($CO_2$) emissions due to travel restrictions, closure of workplaces and other factors that have led to reduced energy consumption [1]. **Table 1** shows the trends of the monthly global $CO_2$ concentration in 2020 and 2021 [2][3]. It was confirmed that the global $CO_2$ concentration was significantly reduced in 2020 due to the COVID-19 pandemic. For example, the global concentration of atmospheric $CO_2$ was 411.66 ppm in October 2020, but increased to 413.93 ppm in October 2021 as a result of the economic recovery from the COVID-19 pandemic, increasing demand for residential electricity, and a lack of clean energy policies [2][3]. Besides that, there have been adverse impacts on solid waste management due to the COVID-19 pandemic. There is a drastic change in the nature of the wastes being generated. A significant increase in medical wastes, plastic wastes (single-use plastic), and food wastes has added an unprecedented load to the waste treatment facilities.

**Table 1.** Global $CO_2$ concentration in 2020 and 2021. Redrawn from the data of $CO_2$ daily [2] and NOAA Earth System Research Laboratory, Global Monitoring Division [3].

| Month | Global $CO_2$ Concentration (Year, 2020) | Global $CO_2$ Concentration (Year, 2021) |
|---|---|---|
| January | 412.43 | 414.77 |
| February | 412.95 | 415.27 |
| March | 413.44 | 415.60 |
| April | 413.86 | 415.92 |
| May | 413.81 | 416.11 |
| June | 412.88 | 415.35 |

| Month | Global $CO_2$ Concentration (Year, 2020) | Global $CO_2$ Concentration (Year, 2021) |
|---|---|---|
| July | 411.17 | 416.96 |
| August | 409.73 | 414.77 |
| September | 410.00 | 413.30 |
| October | 411.66 | 413.93 |
| November | 413.25 | 414.26 |

$CO_2$ emissions and water pollution caused by improper waste management such as plastic waste disposal are the two critical topics that need an urgent solution to protect and save the planet. $CO_2$ released from the industries beyond power generation can be captured using pre-combustion $CO_2$ capture, post-combustion $CO_2$ capture, oxy-fuel combustion, and chemical looping technologies [4][5]. Among these $CO_2$ capture technologies, post-combustion systems such as absorption (using solvent), adsorption (using solid material), cryogenic, and membrane separation have been recognized as mature technologies and have been developed at a large-scale application [5]. Absorption with aqueous alkanolamine solvent is the most promising technology and remains the dominant industrial technology for removal of gases such as $CO_2$ [4]. However, the drawback of the absorption method is related to amine degradation, equipment corrosion, and the generation of volatile degradation compounds [4][5].

The adsorption of $CO_2$ using solid material is an alternative method to amine-based absorption. This is because adsorption has several advantages, such as ease of operation, low energy consumption, good performance for the removal of gas and liquid, and ease of adsorbent regeneration [5][6]. There are several promising adsorbents developed for $CO_2$ adsorption such as activated carbon [7], metal organic frameworks (MOFs) [8], zeolites [9], microporous organic polymer [10], mesoporous carbon material [11], nanoporous silica [12], and carbon nanotubes [13]. The most important characteristics of adsorbents include high surface area, high porosity, high stability, excellent recyclability, and high adsorption capacity [14]. However, the main challenges of some adsorbent materials such as MOFs and nanomaterials are that they are costly and difficult to produce on a large scale, thus causing some adsorbents to be less feasible for industrial applications [15]. Therefore, more research is needed in order to develop a low-cost material with an excellent adsorption capacity that can be used for commercial-scale production. Solid waste is an enormous problem in any part of the world, and conversion of the waste into porous carbon and adsorbents for $CO_2$ capture is an alternative option to reduce waste generation. Due to sustainability considerations, there is a growing trend of using low-cost material as an adsorbent in which plastic waste has been categorized as the potential waste to be transformed as an effective adsorbent to capture $CO_2$. It was proved that adsorbent derived from plastic waste has an excellent performance. For example, Machado et al. [16] investigated the potential of converting plastic waste (polystyrene foams) into magnetic activated carbon for redox supercapacitor application. They reported that magnetic activated carbon derived from plastic waste has a high surface area, excellent chemical and electrical properties and outstanding regeneration performance. In another study, Ilyas et al. [17] used activated carbon derived from waste polyethylene terephthalate and waste polystyrene for the removal of polycyclic aromatic hydrocarbons from industrial wastewater. The study reported that the activated carbon produced had a high surface area, highly porous structure material and produced excellent adsorption efficiency up to 95%.

However, there are very limited reports available in the literature on the potential of carbon-based material derived from waste plastic for $CO_2$ capture. Waste polyethylene terephthalate (PET) is widely used as raw material to be converted into carbon-based material due to PET containing large amounts of carbon. In addition, functional groups such as the OH group found in PET-derived porous carbon will help in increasing $CO_2$ adsorption capacity [18]. For example, Kaur et al. [19] used waste PET and carbonized it into carbon-based material using KOH as activating agent for $CO_2$ capture. The produced carbon-based material has a high surface area (1690 $m^2$/g) and the highest adsorption uptake of 1.31 mmol/g. To convert plastic waste into char (carbon-based material), the raw plastic waste was cut into small sizes and carbonized in a furnace at a temperature of 600 °C under an inert atmosphere (absence of oxygen) [18][19][20][21][22]. Next, the char was modified using physical activation such as $CO_2$ or steam and chemical activation (such as KOH, NaOH, $H_3PO_4$ and

$K_2CO_3$ as activating agent). The modified samples were heated to a temperature between 500 and 800 °C [22]. The physical and chemical activation will help in enhancing the surface properties of char, thus producing a highly porous structure carbon-based material [18][19].

Plastics have emerged to be an inseparable part of our daily lives and are a significant component of our economy due to them being cheap, durable, and lightweight, as well as the fact that they can be used in many applications. Therefore, plastic production has almost reached five hundred billion kilograms in 2018 [23]. The increasing plastic production causes severe negative impacts on the environment, especially in solid waste management [23][24]. An alternative solution to reduce the plastic waste problem is by converting plastic waste into char (solid material) using the pyrolysis process to produce porous material to be used for $CO_2$ capture.

## 2. Overview of Plastic

Plastic is ubiquitous in our daily lives. Therefore, it is difficult to imagine a world without plastic. Plastic material has unique properties, such as being lightweight, flexibility, resistance to corrosion, and the ability to be mixed with different colors, making plastic suitable to be applied in various applications [24][25]. All plastics consist of large molecules of substances called polymers. They consist of many identical small particles that are strong and bound together like a chain. In general, a monomer is a molecule that forms the basic unit of polymers. Polymers, either being produced from natural or synthetic materials, are formed using the polymerization process of many small molecules known as monomers. Specific polymers normally comprise one or two types of monomers [25]. The polymers are formed by joining together many monomers like a long chain of paperclips to form one long molecule [25][26].

Due to the increase in the mass production of synthetic plastics since the 1950s [10], plastic waste disposal has drastically increased, tripling since the 1990s [27]. Plastics are difficult to be broken down into small components and usually can take up to 1000 years to decompose in landfills [28]. People around the world become addicted to single-use plastics, of which 60% end up in landfills thus causing severe environmental problems [29][30]. Every year, there is an increase in plastic waste generation to a current total of three hundred billion kilograms, which is equivalent to the total number of the entire human population [31]. Most plastics will not be destroyed or disappear, but will be broken down into smaller particles. Many of these tiny plastic particles are swallowed by farm animals or fish who mistake them for food, and thus these particles find their way onto our dinner plates. If the current trends continue, our oceans could contain more plastic than fish by 2050 [32][33]. Plastic waste has become a pressing issue of discussion in many countries, such as Malaysia, Thailand, the Philippines, and Indonesia. Many countries have restricted plastic waste imports and introduced several policies to address this problem [34]. Over the year, plastic pollution has become one of the most pressing environmental issues, since the rapid increase in the production of disposable plastic products overwhelms the world's ability to deal with them. Plastics have surprisingly carbon-intense life cycles. The carbon footprint of plastics continues even after being disposed of. The dumping, incinerating, recycling, and composting of these plastic materials (for certain plastics) release $CO_2$ [35]. Therefore, it is important to discuss research on the life cycle of plastics [36][37]. Only 9% of plastic was recycled, 12% was incinerated, and a huge amount of plastic (79%) was gathered in the landfills. Recycling offers the simplest solution, and it has plenty of room for improvement [38]. The public must understand the magnitude of the challenges that each country is facing to overcome this issue [39]. There is a lot of efforts that have been carried out but the more sustainable effort is required to reduce plastic waste and environmental pollution.

## 3. Method for Management and Reducing Plastic Waste

As plastic waste has increased quite rapidly every year, the course of actions to mitigate or recycle plastic waste should be determined immediately. Therefore, by implementing this action, the negative impacts on the environment, either the land or the water, will decrease. Hence, waste management plays an important role in the protection of the environment, covering parts of the collection, transport, recovery, and neutralization of plastic waste [40]. Due to urbanization, the demand for plastic production is increasing because the properties of plastic have advantageous in the food packaging industries, manufacturing industries, the medical world, and other fields [25][26]. The demand for plastic in industries, as well as the number of humans, is growing rapidly, leading to an increase in the utilization of plastic and demand for energy, as they are made from exhaustible fossil fuels such as coal, natural gas or oil [41]. The conventional way has been used to minimize the number of plastic wastes involving landfilling whereby plastics are dumped at a specific land site. This is an ineffective way of reducing plastic waste that causes severe problems to the environment. Landfill sites occupy large areas of land with expensive taxes or tariffs in place to discourage sending waste to these lands [40][41]. This method is quite disadvantageous, as plastic takes time to self-biodegrade since this process uses heat from the sunlight [42]. Therefore, the rate of landfilling keeps growing, while the rate of biodegradable waste increases very slowly. The process of plastic degradation in nature is partitioned into several parts, which are physical, biological and chemical processes [41].

These processes require pressure, humidity, and heat from the sun for physical degradation. Plastic build-up from a chemical compound, which is a hydrocarbon compound procured from petroleum refining, hardens the bond between the monomers. Thus, the degradation process has difficulty proceeding at the ambient temperature (32 °C). Biological degradation by enzymes and bacteria is difficult, and this process takes quite a long time to be completed [43]. Incineration is another method used for plastic waste management. However, incineration is not considered an eco-friendly approach, since hazardous materials are released during this process. The cost is also high for constructing the incineration unit [44].

Furthermore, a recycling method can be applied to reduce the plastic waste problem since many plastics can be recycled. Plastics such as PET and HDPE are recyclable but it is quite costly to recycle them. Hannah and Max [45] stated that only 20 percent of the plastic waste is recycled globally. This indicates that the recycle method has not been receiving attention widely enough to be used as a strategy to reduce plastic waste in many countries. For example, the recycling rate of plastic in Malaysia is about 28%, which is lower than other countries. Awareness regarding plastic waste should be increased and the importance of the 3Rs that is “reuse, reduce and recycle” should be taken seriously to reduce the rate at which plastic waste is polluting the environment [34].

The utilization of plastic waste for recycling is one of the efficient ways to overcome plastic wastage, and it has been delivering a good result as it reduces the production cost and other factors. Plastic waste can be utilized by converting them through the treatment process. These treatments of plastic waste and recycling would be partitioned into four major types, such as primary or re-extrusion, secondary or mechanical based, tertiary or chemically oriented, and quaternary or energy recovery [46][47]. However, each of these offers its own benefits and disadvantages. Primary recycling is known as closed-loop recycling, which is the process of recycling the waste into similar products to the original and use it back in the original application [46]. These newly produced products will have similar characteristics to the original. One of the examples of primary recycling is injection molding to produce low-density polypropylene (LDPE) products. Plastic wastes are mainly recycled from the industry via this technique [46][47]. The secondary recycling technique is mechanical-based, which is recovering plastic waste in plastic manufacturing via physical modification, and it only can be done on single-polymer plastic [48]. Contaminated plastic will cause difficulty in recycling using mechanical techniques due to the degradation and heterogeneity of plastic waste [46][47][48]. In addition, mechanical recycling is expensive and requires a high-energy process as it involves several treatment and preparation steps [49]. One of the examples of mechanical recycling techniques is the construction of pavement blocks using plastic waste such as PE and PP [50]. In addition, tertiary recycling is using plastic waste as feedstock to generate fuels and solid residues [44]. It is an advanced process that converts plastic waste into smaller molecules, which are mostly in liquid or gas forms [46][47]. These molecules are fit to be utilized as a feedstock for the new chemical and plastic production. It is believed that the product that is produced through chemical recycling is beneficial to be used as fuel as it has a high yield of product and is able to minimize waste [46]. The effective way of plastic waste utilization is chemical recycling whereby various products are being produced, such as gases, liquid, and char [49]. Thus, it will be a profitable and sustainable industrial plan of action. The main benefit of chemical recycling is the likelihood of treating heterogeneous and contaminated polymers with a finite use of pre-treatment [48]. Chemical recycling requires hydrogenation, pyrolysis, and gasification techniques, which are the most effective ways to recycle plastic [46][47][48][49].

Pyrolysis is an alternative technique in chemical recycling, as this process takes place in a zero-oxygen condition, leading to thermal cracking and condensation resulting in an increased production of numerous liquids, gases, and solid fractions [51][52]. The difference between pyrolysis with the hydrogenation of plastic and pyrolysis with the gasification of plastic depends on the carbonization method, temperature, and product formed [51][52][50]. The profit of incineration, gasification or decomposition in converting plastic waste will reduce the amount of heat released into the environment. An example of this process is the utilization of waste plastic oil in a diesel engine by catalytic pyrolysis [50][53]. Quaternary recycling involves energy recovery [35]. This refers to the burning of waste to yield energy in the form of heat, steam, and electricity [35]. It is believed that this method is a practical means of waste treatment when the material recovery process fails due to economic limitations. Plastic material has a very high calorific value when it is burned, as it is derived from crude oil, making it a useful energy source [48]. Therefore, heat that is one of the forms of energy recovered by this process can be used for power generation [49]. The pyrolysis oil obtained from the catalytic treatment of polystyrene results in better engine power with a comparable temperature of an engine with a lower amount of carbon monoxide and carbon monoxide emissions, as compared to the uncatalyzed oil and mercantile fuel in gasoline engine [54]. Besides that, char produced from the pyrolysis process of mixed waste plastic will form a porous carbon that can be used in the adsorption of liquid or gas or other applications [55].

### 3.1. Conversion of Plastic Waste into a Carbon-Based Material

In order to reduce the environmental pollution generated from the disposal of used plastic materials, a growing interest has been focused on the conversion of plastic waste into valuable materials [56][57]. Numerous studies have successfully converted plastic waste into porous carbon in various applications, such as that applied in organic and inorganic removal from synthetic and real wastewater [58][59], used in natural gas application [60], nanoporous adsorbents used as electrode material in supercapacitors [61], and porous carbon nanosheets with excellent performance applied in hydrogen storage [62]. However, very limited reports are available on their application in capturing $CO_2$. There are different methods that have been used to transform plastic waste into porous carbons such as using gasification, direct carbonization (physical or chemical activation), hydrothermal carbonization and pyrolysis [18][51]. Among the various technologies available for plastics waste treatment, pyrolysis is one of the most promising methods and the process can be carried out with or without catalysts [63]. Plastics are among the most valuable types of waste, and it is possible to convert plastics directly into useful forms of new adsorbent material, energy, and chemicals for an industry, known as "pyrolysis". Pyrolysis is normally used to generate energy in the form of heat, electricity or fuels, but it could also help to recover other chemicals and materials. Roberts et al. [64] stated that pyrolysis is a thermochemical method in the absence of oxygen to convert biomass or waste material into valuable char or carbon materials, biochar, bio-oil, and syngas. Char or carbon-based material produced from the pyrolysis process is stable charcoal with high carbon content and can be used as a soil amendment. Pyrolysis systems that produce char or carbon-based material and energy (fuel or oil) do not result in pollution, contaminate water supplies or create waste disposal problems [31]. In another study, Scott et al. [65] reported that pyrolysis is a decomposition process of long-chain hydrocarbon (polymer) molecules into smaller sizes (monomer) with the use of high heat (450–800 °C) in a shorter duration. This process, as claimed by the same study, generates products in the form of carbon or char as the residues, as well as volatile hydrocarbons in the form of condensed and non-condensable fuel and as a gaseous fuel. The pyrolysis technique has been investigated by many researchers mainly on the conversion of liquid pyrolysis products into products similar to crude oil [66]. However, there is a limited study exploring the char by-product produced from pyrolysis.

### 3.2. Pyrolysis of Plastic Waste

The pyrolysis process is a process of converting organic material into three phases, which are solid (char), liquid (tar), and gas [67] without involving reaction with oxygen, water and other reagents. As stated by Fakhrhoseini and Dastanian [67], all these phases are immiscible and unprompted. There are several types of pyrolysis of biomass, including fast pyrolysis, slow pyrolysis [68], and microwave pyrolysis. These processes are differentiated by the pyrolysis method, processing time, pyrolysis temperature and the catalyst [69]. However, the processes can be done with or without a catalyst since they only act to increase the reaction rate. The optimum amount of bio-oil yield is obtained when high temperature and high heating rates are applied. Hence, this is a fast pyrolysis process. For slow pyrolysis, a slower heating rate will be applied and the major product for this process is the char [70][71]. Char is a good adsorbent because of its highly porous carbon. As mentioned by Al-Salem et al. [70], pyrolysis is a thermo-chemical plastic waste treatment method that does not contribute to pollution and required less energy and product such as oil and gas. The large-scale experimental set-up of the pyrolysis process involves the process flow to a heat exchanger, condenser, and exhaust stream. For the first side of the exchanger, the condenser with cooling silicon oil in the shell is used while the second side of the exchanger uses water. As the reaction starts, the pyrolysis product enters the tube side of the heat exchanger and the liquid sample bottle is used to accumulate the liquid product while char as the solid product remains in the reactor [67]. An example of a pyrolyzer used is the fluidized bed pyrolyzer with an electrostatic precipitator or with a circulating heat carrier. This pyrolyzer has a good heat transfer rate and a uniform temperature. Moreover, a high amount of bio-oil will be produced, which is up to 75% [72]. However, it requires a small particle size, a large amount of inert gas, and a high operating cost. The other two pyrolyzers are rotating cones and Auger pyrolyzer. For the rotating cone, it has a comparatively simple construction and operation, and a low heat carrier but with a limited capacity. Lastly, the Auger purolyzer is compact, has a simple construction and hence is easy to operate and can be operated at a lower temperature. The disadvantages of the Auger pyrolyzer is that the residence time is long, it has a low bio-oil yield, high yield of char, and limitation for scaling up due to the heat transfer [73]. **Table 2** shows the summary of studies on plastic waste using pyrolysis process. Only a few data reported on the product yields acquired from the thermal treatment at 400–800 °C.

**Table 2.** Summary of studies on plastic waste using pyrolysis process.

| Type of Plastic | Reactor | Pyrolysis Temperature (°C) | Catalyst | Crude Oil(wt%) | Solid Residue (wt%) | Gas (wt%) | Reference |
|---|---|---|---|---|---|---|---|
| PE | Parr mini bench top | 500 | None | 93 | 0 | 7 | [31][73] |
| PP | | | | 95 | 5 | 5 | |
| PS | | | | 71 | 27 | 2 | |
| PET | | | | 15 | 53 | 32 | |
| Mixed | | | | 90 | 5 | 5 | |
| PE | Activated carbon bed | 515–795 | None | 88–96 | 5.5 | 2 | [65][73] |
| LDPE | Fixed-bed tubular flow reactor | 425 | HZSM-5 $SiO_2$-$Al_2O_3$ | | | | [73][74] |
| HDPE | Continuous reactor | 520 | HZSM-5 | | | | [66][73] |
| PET | Fixed bed | 500 | - | 23.1 | 0 | 76.9 | [51] |

### 3.3. Modification of Plastic Wastes for $CO_2$ Capture

For the pyrolysis process, the most important parameters that need to be considered are the pyrolysis temperature, treatment (heating) time, and heating rate. After the first cycle of pyrolysis, the produced sample (char) needs to be modified with a chemical activation treatment to improve the surface properties of the material. Then, the modified sample needs to be heated again using a pyrolysis technique. The physicochemical properties of the char produced from pyrolysis, such as elemental analysis (carbon, hydrogen, nitrogen, and oxygen content), surface area and pore size, functional groups, surface morphology, and thermal stability, are important to monitor [51]. From the results of the physicochemical properties, the adsorbent material that produces high performance in terms of high carbon content, large surface area and pore size, and high thermal stability has the potential to be used to study $CO_2$ adsorption. In general, the overall adsorption process using plastic waste as an adsorbent is illustrated in **Figure 1**.

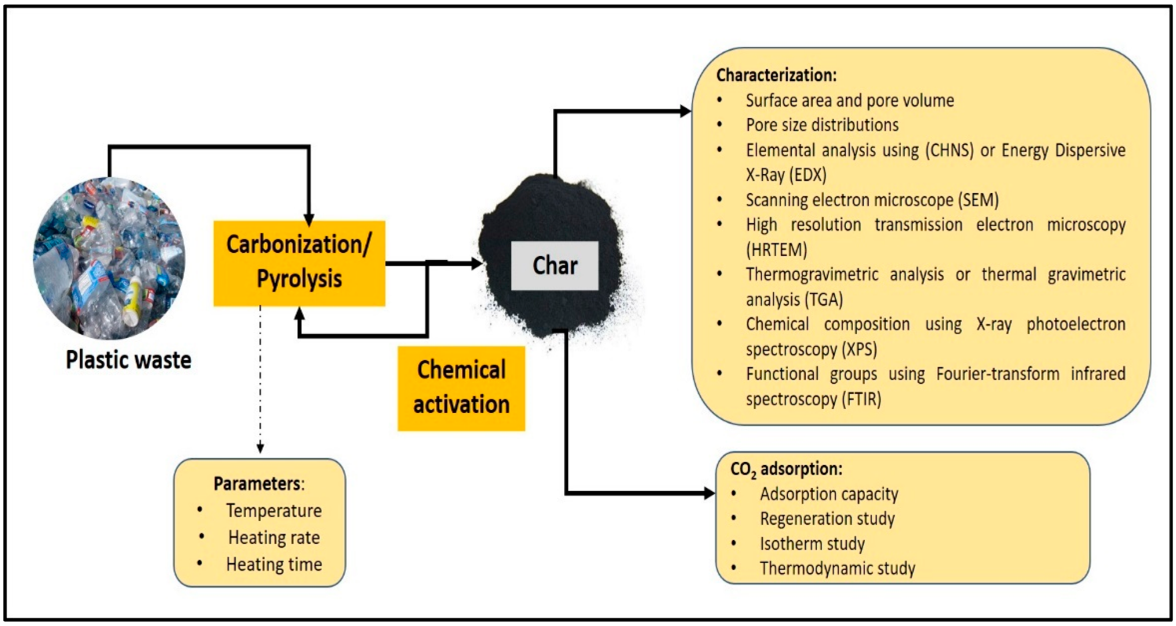

**Figure 1.** Overall adsorption process using plastic waste as an adsorbent.

### 3.4. $CO_2$ Adsorption Performance

There are only a few literature studies reported on the use of porous carbon derived from plastic waste in the application of $CO_2$ (**Table 3**). PET plastic waste is considered a low-cost material and effective to capture $CO_2$ due to the high carbon and oxygen content confirmed by the elemental composition of XPS analysis. **Table 3** shows the previously published studies that used PET plastic waste as a raw material to produce porous carbon material. For example, Arenillas et al. [75] investigated the potential of carbon material derived from PET bottles as an adsorbent to capture $CO_2$ using the carbonization process at 500 °C. The study reported that the highest $CO_2$ uptake was achieved at 1.09 mmol/g using adsorption temperature at 25 °C. Adibfar et al. [76] modified the PET waste with various types of activating agents, such as KOH, $H_3PO_4$, $ZnCl_2$, and $H_2SO_4$, and compared their adsorption capacity performances. The team reported that the porous carbon modified with alkaline hydroxides as activating agents showed the highest adsorption capacity, while the acidic activating agents showed the lowest adsorption capacity. This is because KOH activation significantly increases the surface area and porosity of the porous carbon, thus enhancing the adsorption capacity. In another study, Moura et al. [77] studied the potential of nanocarbons derived from PET waste by physical activation to remove $CO_2$. The porous carbons mainly contain micropores and showed a high surface area, high pore volume, and a well-developed porous structure. Using a similar method, Parra et al. [78] used PET waste to convert the waste into valuable products using the pyrolysis process. The product obtained after the pyrolysis process is gas (58%), terephthalic acid (20%), and char (22%). The char produced from pyrolysis was used as an adsorbent. The highest surface area was found to be at 2468 $m^2$/g, which was obtained at an optimum pyrolysis temperature of 925 °C and a flow rate of 10 mL/min. The highest adsorption capacity of 4.04 mmol/g was achieved at an optimum adsorption temperature of 25 °C. Kaur et al. [19] conducted a study to convert waste PET into carbonized char and then modified the surface properties of the material using KOH to enhance the $CO_2$ adsorption capacity. The maximum adsorption capacity of 1.31 mmol/g was obtained at an optimum adsorption temperature of 30 °C and a $CO_2$ concentration of 12.5%. The regeneration study showed that the modified adsorbent can be regenerated up to 4 cycles without reducing the adsorption capacity. The adsorption kinetics and the isotherm data follow the fractional-order kinetic model and Freundlich isotherm model. In addition, the negative values of enthalpy and Gibbs free energy suggest that these adsorption processes were exothermic and thus confirm the feasibility of the process and the spontaneous nature of the adsorption. Isosteric heat of adsorption (Qst) is an important element in thermodynamics and is used to measure the heat released upon the adsorption [79][80]. For the carbonized PET-KOH sample, the average Qst value obtained was at −12.08 kJ/mol, and the value tends to be more negative with changes in the temperature, demonstrating the exothermic nature of the adsorption process [79].

**Table 3.** Summary of plastic waste as adsorbent for $CO_2$ capture.

| Type of Plastic | Activating Agent | Characterization | Surface Area, $m^2$/g | $CO_2$ Adsorption Capacity, mmol/ g | Optimum Operating Condition | References |
|---|---|---|---|---|---|---|
| Polyethylene terephthalate (PET) | KOH | CHN, FTIR, XRD, SEM, HRTEM, BET and XPS techniques | 1690 | 1.31 | Temperature, 30 °C and 12.5% $CO_2$ concentration | [19] |
| PET | KOH or NaOH | XRD, SEM, HRTEM, BET and XPS techniques | 1812 | 4.42 | Temperature, 25 °C | [18] |
| PET | KOH | BET, XPS, FTIR, and EDX analysis | 1690 | 1.35 | Temperature, 30 °C and 12.5% $CO_2$ concentration | [81] |

| Type of Plastic | Activating Agent | Characterization | Surface Area, $m^2$/g | $CO_2$ Adsorption Capacity, mmol/ g | Optimum Operating Condition | References |
|---|---|---|---|---|---|---|
| PET | KOH | BET, XPS, SEM, HRTEM, TPD and CHN analysis | 1690 | 2.31 | Temperature, 30 °C and 12.5% $CO_2$ concentration | [82] |
| WEPS (waste expanded polystyrene) | - | BET, XPS, SEM, HRTEM, TPD and CHN analysis | 777 | 2.52 | Temperature, 30 °C | [83] |
| PET | KOH | BET, XPS, SEM, HRTEM, FTIR analysis | 1165 | 4.58 | Temperature, 25 °C | [78] |
| PET | KOH | BET, XPS, HRTEM, FTIR analysis | - | 1.25 | Temperature, 25 °C | [75] |

## References


1. IEA. After Steep Drop in Early 2020, Global Carbon Dioxide Emissions Have Rebounded Strongly. 2021. Available online: https://www.iea.org/news/after-steep-drop-in-early-2020-global-carbon-dioxide-emissions-have-rebounded-strongly (accessed on 1 August 2021).
2. Daily CO2. Available online: https://www.co2.earth/daily-co2 (accessed on 12 October 2021).
3. NOAA. Trends in Atmospheric Carbon Dioxide. Global Monitoring Laboratory Earth System Research Laboratories. National Oceanic & Atmospheric Administration (NOAA Research). 2021. Available online: https://gml.noaa.gov/ccgg/trends/ (accessed on 6 November 2021).
4. Lisbona, P.; Bailera, M.; Peña, B.; Romeo, L.M. Chapter 22—Integration of CO2 capture and conversion. In Advances in Carbon Capture; Rahimpour, M.R., Farsi, M., Makarem, M.A., Eds.; Woodhead Publishing: Sawston, UK, 2020; pp. 503–522.
5. Leung, D.Y.C.; Caramanna, G.; Maroto-Valer, M.M. An overview of current status of carbon dioxide capture and storage technologies. Renew. Sustain. Energy Rev. 2014, 39, 426–443.
6. Dissanayake, P.D.; You, S.; Igalavithana, A.D.; Xia, Y.; Bhatnagar, A.; Gupta, S.; Kua, H.W.; Kim, S.; Kwon, J.H.; Tsang, D.C.W.; et al. Biochar-based adsorbents for carbon dioxide capture: A critical review. Renew. Sustain. Energy Rev. 2020, 119, 109582.
7. Mallesh, D.; Anbarasan, J.; Mahesh Kumar, P.; Upendar, K.; Chandrashekar, P.; Rao, B.V.S.K.; Lingaiah, N. Synthesis, characterization of carbon adsorbents derived from waste biomass and its application to CO2 capture. Appl. Surf. Sci. 2020, 530, 147226.
8. Qasem, N.A.A.; Ben-Mansour, R. Adsorption breakthrough and cycling stability of carbon dioxide separation from CO2/N2/H2O mixture under ambient conditions using 13X and Mg-MOF-74. Appl. Energy 2018, 230, 1093–1107.
9. Davarpanah, E.; Armandi, M.; Hernández, S.; Fino, D.; Arletti, R.; Bensaid, S.; Piumetti, M. CO2 capture on natural zeolite clinoptilolite: Effect of temperature and role of the adsorption sites. J. Environ. Manag. 2020, 275, 111229.
10. Xu, C.; Yu, G.; Yuan, J.; Strømme, M.; Hedin, N. Microporous organic polymers as CO2 adsorbents: Advances and challenges. Mater. Today Adv. 2020, 6, 100052.
11. Zhao, P.; Yin, Y.; Cheng, W.; Xu, X.; Yang, D.; Yuan, W. Development of facile synthesized mesoporous carbon composite adsorbent for efficient CO2 capture. J. CO2 Util. 2021, 50, 101612.

12. Chen, C.; Bhattacharjee, S. Trimodal nanoporous silica as a support for amine-based CO2 adsorbents: Improvement in adsorption capacity and kinetics. Appl. Surf. Sci. 2017, 396, 1515–1519.

13. Rahimi, K.; Riahi, S.; Abbasi, M.; Fakhroueian, Z. Modification of multi-walled carbon nanotubes by 1,3-diaminopropan e to increase CO2 adsorption capacity. J. Environ. Manag. 2019, 242, 81–89.

14. Kamran, U.; Park, S.J. Chemically modified carbonaceous adsorbents for enhanced CO2 capture: A review. J. Clean. P rod. 2021, 290, 125776.

15. Petrovic, B.; Gorbounov, M.; Masoudi Soltani, S. Influence of surface modification on selective CO2 adsorption: A techn ical review on mechanisms and methods. Microporous Mesoporous Mater. 2021, 312, 110751.

16. Machado, N.C.F.; de Jesus, L.A.M.; Pinto, P.S.; de Paula, F.G.F.; Alves, M.O.; Mendes, K.H.A.; Mambrini, R.V.; Barrred a, D.; Rocha, V.; Santamaría, R.; et al. Waste-polystyrene foams-derived magnetic carbon material for adsorption and r edox supercapacitor applications. J. Clean. Prod. 2021, 313, 127903.

17. Ilyas, M.; Ahmad, W.; Khan, H. Utilization of activated carbon derived from waste plastic for decontamination of polycycl ic aromatic hydrocarbons laden wastewater. Water Sci. Technol. 2021, 84, 609–631.

18. Yuan, X.; Lee, J.G.; Yun, H.; Deng, S.; Kim, Y.J.; Lee, J.E.; Kwak, S.K.; Lee, K.B. Solving two environmental issues sim ultaneously: Waste polyethylene terephthalate plastic bottle-derived microporous carbons for capturing CO2. Chem. En g. J. 2020, 397, 125350.

19. Kaur, B.; Gupta, R.K.; Bhunia, H. Chemically activated nanoporous carbon adsorbents from waste plastic for CO2 capt ure: Breakthrough adsorption study. Microporous Mesoporous Mater. 2019, 282, 146–158.

20. Minakshi, M.; Meyrick, D.; Appadoo, D. Maricite (NaMn1/3Ni1/3Co1/3PO4)/activated carbon: Hybrid capacitor. Energy Fuels 2013, 27, 3516–3522.

21. Sajjadi, B.; Chen, W.Y.; Egiebor, N.O. A comprehensive review on physical activation of biochar for energy and environ mental applications. Rev. Chem. Eng. 2019, 35, 735–776.

22. Wickramaarachchi, W.A.M.K.P.; Minakshi, M.; Gao, X.; Dabare, R.; Wong, K.W. Hierarchical porous carbon from mang o seed husk for electro-chemical energy storage. Chem. Eng. J. Adv. 2021, 8, 100158.

23. Shrivastava, A. 7—Environmental aspects of plastics. In Introduction to Plastics Engineering; Shrivastava, A., Ed.; Willi am Andrew Publishing: Burlington, MA, USA, 2018; pp. 207–232.

24. Shrivastava, A. 3—Plastic properties and testing. In Introduction to Plastics Engineering; Shrivastava, A., Ed.; William A ndrew Publishing: Burlington, MA, USA, 2018; pp. 49–110.

25. Flores-Tlacuahuac, A.; Saldívar-Guerra, E.; Guerrero-Santos, R. Dynamic modelling, nonlinear parameter fitting and se nsitivity analysis of a living free-radical polymerization reactor. In Computer Aided Chemical Engineering; Asprey, S.P., Macchietto, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2003; pp. 21–39.

26. Evode, N.; Qamar, S.A.; Bilal, M.; Barceló, D.; Iqbal, H.M.N. Plastic waste and its management strategies for environm ental sustainability. Case Stud. Chem. Environ. Eng. 2021, 4, 100142.

27. Tuladhar, R.; Yin, S. 21—Sustainability of using recycled plastic fiber in concrete. In Use of Recycled Plastics in Eco-eff icient Concrete; Pacheco-Torgal, F., Khatib, J., Colangelo, F., Tuladhar, R., Eds.; Woodhead Publishing: Burlington, M A, USA, 2019; pp. 441–460.

28. UN. Our Planet Is Drowning in Plastic Pollution, UN Environment. 2018. Available online: https://www.unep.org/interacti ve/beat-plastic-pollution/ (accessed on 1 September 2021).

29. Szaky, T. Outsmart Waste: The Modern Idea of Garbage and How to Think Our Way Out of It; Berrett-Koehler Publisher s: Oakland, CA, USA, 2014; p. 168.

30. Thiounn, T.; Smith, R.C. Advances and approaches for chemical recycling of plastic waste. J. Polym. Sci. 2020, 58, 134 7–1364.

31. Williams, P.T.; Slaney, E. Analysis of products from the pyrolysis and liquefaction of single plastics and waste plastic mi xtures. Resour. Conserv. Recycl. 2007, 51, 754–769.

32. Ellen MacArthur Foundation. The New Plastics Economy, Rethinking the Future of Plastics. Available online: http://www 3.weforum.org/docs/WEF_The_New_Plastics_Economy.pdf (accessed on 1 September 2021).

33. Kosior, E.; Crescenzi, I. Chapter 16—Solutions to the plastic waste problem on land and in the oceans. In Plastic Wast e and Recycling; Letcher, T.M., Ed.; Academic Press: Cambridge, MA, USA, 2020; pp. 415–446.

34. Asmuni, S.; Hussin, N.B.; Khalili, J.M.; Zain, Z.M. Public participation and effectiveness of the no plastic bag day progra m in Malaysia. Procedia Soc. Behav. Sci. 2015, 168, 328–340.

35. Merrington, A. 9—Recycling of Plastics. In Applied Plastics Engineering Handbook, 2nd ed.; Kutz, M., Ed.; William Andr ew Publishing: Burlington, MA, USA, 2017; pp. 167–189.

36. Bernardo, C.A.; Simões, C.L.; Pinto, L.M.C. Environmental and economic life cycle analysis of plastic waste managem ent options: A review. AIP Conf. Proc. 2016, 1779, 140001.

37. Khoo, H.H. LCA of plastic waste recovery into recycled materials, energy and fuels in Singapore. Resour. Conserv. Rec ycl. 2019, 145, 67–77.

38. Barbara, U.O.C.-S. Plastic's Carbon Footprint: Researchers Conduct First Global Assessment of the Life Cycle Greenh ouse Gas Emissions from Plastics; ScienceDaily: Rockville, MD, USA, 2019.

39. Jayaraman, K.; Haron, H.; Sung, G.B.; Lin, S.K. Consumer reflections on the usage of plastic bags to parcel hot edible i tems: An empirical study in Malaysia. J. Clean. Prod. 2011, 19, 1527–1535.

40. Bujak, J.W. Thermal utilization (treatment) of plastic waste. Energy 2015, 90, 1468–1477.

41. Quesada, L.; Calero, M.; Martín-Lara, M.A.; Pérez, A.; Blázquez, G. Characterization of fuel produced by pyrolysis of pl astic film obtained of municipal solid waste. Energy 2019, 186, 115874.

42. Scalenghe, R. Resource or waste? A perspective of plastics degradation in soil with a focus on end-of-life options. Heliy on 2018, 4, e00941.

43. Thahir, R.; Altway, A.; Susianto, S.R.J. Production of liquid fuel from plastic waste using integrated pyrolysis method wit h refinery distillation bubble cap plate column. Energy Rep. 2019, 5, 70–77.

44. Abdel-Shafy, H.I.; Mansour, M.S.M. Solid waste issue: Sources, composition, disposal, recycling, and valorization. Egy pt. J. Pet. 2018, 27, 1275–1290.

45. Hannah, R.; Max, R. Plastic Pollution. 2018. Available online: https://ourworldindata.org/plastic-pollution (accessed on 1 0 September 2021).

46. Al-Salem, S.M.; Lettieri, P.; Baeyens, J. The valorization of plastic solid waste (PSW) by primary to quaternary routes: F rom re-use to energy and chemicals. Prog. Energy Combust. Sci. 2010, 36, 103–129.

47. Singh, N.; Hui, D.; Singh, R.; Ahuja, I.P.S.; Feo, L.; Fraternali, F. Recycling of plastic solid waste: A state of art review a nd future applications. Compos. Part B: Eng. 2017, 115, 409–422.

48. Al-Salem, S.M.; Lettieri, P.; Baeyens, J. Recycling and recovery routes of plastic solid waste (PSW): A review. Waste M anag. 2009, 29, 2625–2643.

49. Awasthi, A.; Shivashankar, M.; Majumder, S. Plastic solid waste utilization technologies: A Review. IOP Conf. Ser. Mate r. Sci. Eng. 2017, 263, 022024.

50. Tulashie, S.K.; Boadu, E.K.; Kotoka, F.; Mensah, D. Plastic wastes to pavement blocks: A significant alternative way to reducing plastic wastes generation and accumulation in Ghana. Constr. Build. Mater. 2020, 241, 118044.

51. Anuar Sharuddin, S.D.; Abnisa, F.; Wan Daud, W.M.A.; Aroua, M.K. A review on pyrolysis of plastic waste. Energy Conv ers. Manag. 2016, 115, 308–326.

52. Abnisa, F.; Wan Daud, W.M.A. A review on co-pyrolysis of biomass: An optional technique to obtain a high-grade pyroly sis oil. Energy Convers. Manag. 2014, 87, 71–85.

53. Dillikannan, D.; Gopal, R.B.K.; Poures, M.; Sethuramasamyraja, B. Utilization of waste plastic oil in diesel engines: A re view. Rev. Environ. Sci. Bio/Technol. 2019, 18, 681–697.

54. Budsaereechai, S.; Hunt, A.; Ngernyen, Y. Catalytic pyrolysis of plastic waste for the production of liquid fuels for engin es. RSC Adv. 2019, 9, 5844–5857.

55. Liu, J.; Chen, X.; Jiang, Z.; Wen, X.; Mijowska, E.; Tang, T. Converting real-world mixed waste plastics into porous carb on nanosheets with excellent performance in the adsorption of an organic dye from wastewater. J. Mater. Chem. A: Mat er. Energy Sustain. 2015, 3, 341–351.

56. Mishra, R.K.; Maria, H.J.; Joseph, K.; Thomas, S. 1—Basic structural and properties relationship of recyclable microfibr illar composite materials from immiscible plastics blends: An introduction. In Micro and Nano Fibrillar Composites (MFC s and NFCs) from Polymer Blends; Mishra, R.K., Thomas, S., Kalarikkal, N., Eds.; Woodhead Publishing: Burlington, M A, USA, 2017; pp. 1–25.

57. Parra, J.B.; Ania, C.O.; Arenillas, A.; Rubiera, F.; Pis, J.J. High value carbon materials from PET recycling. Appl. Surf. S ci. 2004, 238, 304–308.

58. Wankasi, D.; Dikio, E.D. Polyvinyl chloride waste as an adsorbent for the sorption of from aqueous solution. J. Chem. 2 014, 2014, 817527.

59. Zhang, H.; Pap, S.; Taggart, M.A.; Boyd, K.G.; James, N.A.; Gibb, S.W. A review of the potential utilisation of plastic waste as adsorbent for removal of hazardous priority contaminants from aqueous environments. Environ. Pollut. 2020, 258, 113698.
60. Yuliusman, Y.; Nasruddin, N.; Sanal, A.; Bernama, A.; Haris, F.; Ramadhan, I.T. Preparation of activated carbon from waste plastics polyethylene terephthalate as adsorbent in natural gas storage. IOP Conf. Ser. Mater. Sci. Eng. 2017, 176, 012055.
61. Utetiwabo, W.; Yang, L.; Tufail, M.K.; Zhou, L.; Chen, R.; Lian, Y.; Yang, W. Electrode materials derived from plastic wastes and other industrial wastes for supercapacitors. Chin. Chem. Lett. 2020, 31, 1474–1489.
62. Gong, J.; Michalkiewicz, B.; Chen, X.; Mijowska, E.; Liu, J.; Jiang, Z.; Wen, X.; Tang, T. Sustainable conversion of mixed plastics into porous carbon nanosheets with high performances in uptake of carbon dioxide and storage of hydrogen. ACS Sustain. Chem. Eng. 2014, 2, 2837–2844.
63. Singh, T.S.; Verma, T.N.; Singh, H.N. A lab scale waste to energy conversion study for pyrolysis of plastic with and without catalyst: Engine emissions testing study. Fuel 2020, 277, 118176.
64. Roberts, K.G.; Gloy, B.A.; Joseph, S.; Scott, N.R.; Lehmann, J. Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. Environ. Sci. Technol. 2010, 44, 827–833.
65. Scott, D.S.; Czernik, S.R.; Piskorz, J.; Radlein, D.S.A.G. Fast pyrolysis of plastic waste. Energy Fuels 1990, 4, 407–411.
66. Miskolczi, N.; Angyal, A.; Bartha, L.; Valkai, I. Fuels by pyrolysis of waste plastics from agricultural and packaging sectors in a pilot scale reactor. Fuel Process. Technol. 2009, 90, 1032–1040.
67. Fakhrhoseini, S.; Dastanian, M. Predicting pyrolysis products of PE, PP, and PET using NRTL activity coefficient model. J. Chem. 2013, 2013, 487676.
68. Caldwell, S.J.; Al-Duri, B.; Sun, N.; Sun, C.G.; Snape, C.E.; Li, K.; Wood, J. Carbon dioxide separation from nitrogen/hydrogen mixtures over activated carbon beads: Adsorption isotherms and breakthrough studies. Energy Fuels 2015, 29, 3796–3807.
69. Aishwarya, K.N.; Sindhu, N. Microwave assisted pyrolysis of plastic waste. Procedia Technol. 2016, 25, 990–997.
70. Al-Salem, S.M.; Antelava, A.; Constantinou, A.; Manos, G.; Dutta, A. A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). J. Environ. Manag. 2017, 197, 177–198.
71. Lehmann, J.; Gaunt, J.; Rondon, M. Bio-char sequestration in terrestrial ecosystems—A review. Mitig. Adapt. Strateg. Glob. Chang. 2006, 11, 403–427.
72. Yang, J.; Yue, L.; Hu, X.; Wang, L.; Zhao, Y.; Lin, Y.; Sun, Y.; DaCosta, H.; Guo, L. Efficient CO2 capture by porous carbons derived from coconut shell. Energy Fuels 2017, 31, 4287–4293.
73. Kunwar, B.; Cheng, H.N.; Chandrashekaran, S.R.; Sharma, B.K. Plastics to fuel: A review. Renew. Sustain. Energy Rev. 2016, 54, 421–428.
74. Uemichi, Y.; Nakamura, J.; Itoh, T.; Sugioka, M.; Garforth, A.A.; Dwyer, J. Conversion of Polyethylene into Gasoline-Range Fuels by Two-Stage Catalytic Degradation using silica−alumina and HZSM-5 zeolite. Ind. Eng. Chem. Res. 1999, 38, 385–390.
75. Arenillas, A.; Rubiera, F.; Parra, J.B.; Ania, C.O.; Pis, J.J. Surface modification of low-cost carbons for their application in the environmental protection. Appl. Surf. Sci. 2005, 252, 619–624.
76. Adibfar, M.; Kaghazchi, T.; Asasian, N.; Soleimani, M. Conversion of Poly (Ethylene Terephthalate) waste into activated carbon: Chemical activation and characterization. Chem. Eng. Technol. 2014, 37, 979–986.
77. Moura, P.A.S.; Vilarrasa-Garcia, E.; Maia, D.A.S.; Bastos-Neto, M.; Ania, C.O.; Parra, J.B.; Azevedo, D.S.C. Assessing the potential of nanoporous carbon adsorbents from polyethylene terephthalate (PET) to separate CO2 from flue gas. Adsorption 2018, 24, 279–291.
78. Parra, J.B.; Ania, C.O.; Arenillas, A.; Pis, J.J. Textural characterisation of activated carbons obtained from poly (ethylene terephthalate) by carbon dioxide activation. In Studies in Surface Science and Catalysis; Rodriguez-Reinoso, F., McEnaney, B., Rouquerol, J., Unger, K., Eds.; Elsevier: Amsterdam, The Netherlands, 2002; pp. 537–543.
79. Cen, Q.; Fang, M.; Wang, T.; Majchrzak-Kucęba, I.; Wawrzyńczak, D.; Luo, Z. Thermodynamics and regeneration studies of CO2 adsorption on activated carbon. Greenh. Gases: Sci. Technol. 2016, 6, 787–796.
80. Mukherjee, S.; Kumar, A.; Zaworotko, M.J. 2—Metal-organic framework-based carbon capture and purification technologies for clean environment. In Metal-Organic Frameworks (MOFs) for Environmental Applications; Ghosh, S.K., Ed.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 5–61.

81. Yuan, X.; Li, S.; Jeon, S.; Deng, S.; Zhao, L.; Lee, K.B. Valorization of waste polyethylene terephthalate plastic into N-doped microporous carbon for CO2 capture through a one-pot synthesis. J. Hazard. Mater. 2020, 399, 123010.
82. Kaur, B.; Singh, J.; Gupta, R.K.; Bhunia, H. Porous carbons derived from polyethylene terephthalate (PET) waste for CO2 capture studies. J. Environ. Manag. 2019, 242, 68–80.
83. Fu, Z.; Mohamed, I.M.A.; Li, J.; Liu, C. Novel adsorbents derived from recycled waste polystyrene via cross-linking reaction for enhanced adsorption capacity and separation selectivity of CO2. J. Taiwan Inst. Chem. Eng. 2019, 97, 381–388.

---