J. Integr. Sci. Technol. 2025, 13(6), 1140

Journal of Integrated
SCIENCE & TECHNOLOGY

Molecular innovations in Plastic fuel toward a sustainable energy future and waste mitigation

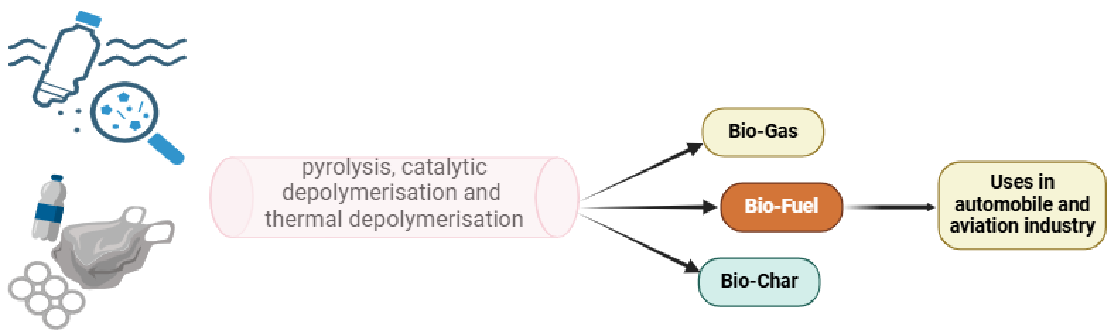
Atreyi Pramanik[1,2], Rajendra Prasad[3], Ajay Singh[1], Pardeep Yadav[1*], Saurabh Kumar Jha[4,5], Sunil Kumar Jaiswal[6], Kushi Anand[7*]

[1]School of Applied and Life Sciences, Uttaranchal University, Dehradun, Uttarakhand, India. [2]Division of Research and Innovation, Uttaranchal University, Dehradun 248007, Uttarakhand, India. [3]School of Agriculture, Uttaranchal University, Dehradun, Uttarakhand, India. [4]Department of Zoology, Kalindi College, University of Delhi, India. [5]Department of Biotechnology Engineering and Food Technology, Chandigarh University, Mohali, 140413, India. [6]Department of Biotech and Bioengineering, School of Biosciences and Technology, Galgotias University, Greater Noida, India. [7]Depatment of Life Sciences, Kristu Jayanti College (Autonomous), Bangalore, India.

Submitted on: 22-Oct-2024, Accepted and Published on: 19-May-2025

Review Article

ABSTRACT



The global issue of plastic waste (PW) presents a persistent environmental challenge, necessitating the adoption of effective and sustainable new mitigation strategies. One promising approach involves converting plastic waste into fuel, which not only alleviates the burden of waste management but also offers a more environmentally friendly method of meeting energy demands. This review examines the sustainable transformation of plastic waste into fuel, with a particular focus on emerging innovative technologies such as pyrolysis, catalytic processes, and thermal depolymerization. The effectiveness of these methods in converting PW into alternative fuels provides basis of development of alternate plastic fuel derived from waste. Additionally, industries involvement in this process can implement PW-to-fuel initiatives to enhance long-term sustainability. This study delves in achieving a sustainable trajectory for plastic along with reducing environmental harm, thus posing the broader arena of relationship with waste and energy to foster sustainability, resilience, and prosperity for future generations.

Keywords: Alternate fuel production, Bioenergy, Biofuel production, Depolymerization, Gasification, Plastic Pollution, Pyrolysis

INTRODUCTION

The rising global crisis regarding plastic waste has led to an insistent search for innovative solutions to control environmental contamination and address energy sustainability issues.[1] One of the latest procedures that has attracted the scientific community is converting plastic trash into renewable energy, specifically alternate fuels. With an emphasis on their potential as a sustainable replacement for fossil fuels, the current review attempts to offer a thorough examination of the various technologies and procedures involved in turning plastic trash into alternate fuels.[2] Since plastic garbage endangers ecosystems, wildlife, and human health, it is one of the most important environmental issues of the twenty-first century. The World Bank projects that by 2050, there will be 576 million tons of plastic garbage produced worldwide, up from an estimated 242 million tons in 2016.[3] Plastic trash is a global environmental concern that poses several challenges due to its large accumulation in landfills, oceans, and ecosystems.[4] Global plastic production shows continuous growth at an 8.4 percent average annual increase since 1950.[5] Plastic manufacturing volume reached 0.36 billion tons in 2018 while forecasting shows it will surpass half

[*]Corresponding Author: Kushi Anand, Department of Life Sciences, Kristu Jayanti College (Autonomous), Bangalore, India 560077 and Pardeep Yadav, School of Applied and Life Sciences, Uttaranchal University, Dehradun, Uttarakhand
Tel: +917259400581; Email: Kushi.a@kristujayanti.com; par.yadav2011@gmail.com

Cite as: *J. Integr. Sci. Technol., 2025, 13(6), 1140.*
URN:NBN:sciencein.jist.2025.v13.1140
DOI:10.62110/sciencein.jist.2025.v13.1140

billion tons by 2025. However, approximately 60% of PW is not recycled and accumulates in the environment.[1] The most commonly used types of plastics include polyvinyl chloride (PVC), polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyurethane (PUR), and polystyrene (PS). This continuously growing environmental burden of PW inspired the scientific community and environmentalists to come up with innovative ideas to deal with this upcoming problem. Rise in carbon emission due to traditional disposal methods like landfilling and incineration, led to environmental damage and worsened the situation, making it more life-threatening.[6] A lion's share of white polymers is dumped off in landfills, incinerators, or in the marine system. Where it can remain for hundreds of years and release dangerous toxins such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs, heavy metals, toxic carbon, oxygen-based free radicals and greenhouse gases (GHGs)[7] whereas, only a small portion of PW is recycled.[8] Transforming PW into renewable energy, like alternate fuels, is one way to alleviate the problem[9] potentially. Alternate fuels are made from biomass, either liquid or gaseous, that can be added to or substituted for fossil fuels in industrial, power generating, and transportation uses. Related to fossil fuels, alternate fuels offer benefits, including reduced GHG emissions, increased energy security, and plausible rural growth.[10] Production of alternate fuel from plastic trash by incorporating methods like pyrolysis, gasification, and liquefaction might be a method to deal with this twin evil. Using such technologies, plastic polymers of various forms could be converted into useful products that in their liquid state such as hydrocarbons are usable as fuels in vehicles or as feedstock for chemical syntheses.[11] Alternate fuel production reduces environmental degradation by diversifying PW from burn facilities and landfills and reducing reliance on finite fossil fuel reserves by utilizing plastic trash energy.[12] Moreover, PW can be converted into alternate fuels using various processes and techniques; including pyrolysis, gasification, liquefaction, fermentation, and transesterification.[13] These technologies vary in feedstock features, working environments, product yields and quality, and economic and environmental impacts.[14] By utilizing bioenergy from agro-industrial wastes, which form one of the significant sources of biomass, there is a potential to mitigate the continuous use of fossil fuels and pollution of the environment.[2] A thorough review of current technology practices between these techniques becomes vital because it allows us to identify the research obstacles and discover possibilities for advancement in future. This review intends to provide a critical analysis on the new developments, the scope for the production of alternate fuel from PW, its origin, types, and composition. Finally, we discuss the opportunities and challenges associated with their collection and pre-treatment.

CHEMICAL PROPERTIES OF PLASTIC

The Society of Plastic Industry (SPI) has categorized plastics into seven classes according to their chemical structures and uses e.g.PET, PS, LDPE, PVC, PP, and HDPE.[13] Plastics are categorized by their diverse chemical properties rooted in composition and structure which exhibit a wide array of features crucial for various applications. However, the polymer structure, determined by monomers and chain arrangement, influences properties like strength, flexibility, and thermal stability.[14] Thermal stability varies with the plastics where few form of plastic resist high temperatures, while others soften and melt easily; this is very critical for processes exposed to high temperatures.[7] Chemical resistance also varies because some are resistant to all chemicals, while others can be easily converted into useful product; therefore play a key role in extreme conditions. Mechanical properties, such as strength, stiffness, and elasticity are determined by polymer chain weight and additives, while optical properties define transparency, UV resistance, and reflectivity to determine their suitability for applications that include windows and lenses.[15] Plastics may own insulating or conductive properties, essential for electrical applications. Environmental degradation, caused by factors like UV radiation and moisture, can alter physical and mechanical properties over time. Understanding these properties is vital for proper selection, applications, addressing challenges related to recycling, disposal, and environmental sustainability.[16]

PLASTIC WASTE – THE SILENT PANDEMIC

The global manufacturing of synthetic plastics has increased to 400 million tons and more than half of these materials is sent to landfills while the rest undergo recycling processes. Approximately, 15 million tons of PW find their way up to the ocean annually. About two-third of it comes from land-based resources such as trash abandoned on the beaches, washed into the rivers and sewers or left behind in the cities. Inadequate disposal down the toilets, poorly maintained landfills, industrial accidents, and waste receptacles close to coasts adds to the issue making it more grave.[17] Predominantly, these discarded items are single-use plastics such as beverage containers, polythene bags, ear bud, feminine hygiene products, and hospital and laboratory waste. A major issue linked to PW is its durability and enduring presence in nature. The decomposition process of most plastics spans hundreds to thousands of years, resulting in their build-up in landfills, water bodies, and ecosystems. This build-up not only diminishes the visual appeal of landscapes but also presents significant dangers to wildlife, marine life, and human well-being.[1] Despite incineration being utilized as a waste disposal method, its environmental impact is concerning. For instance, in the United States alone, plastic incineration emitted 5.9 million metric tons (MT) of carbon dioxide in 2015, with projections anticipating figures to soar to 49 million MT by 2030 and 91 million MT by 2050.[18]

India ranks as the fifth-largest producer of PW globally. To combat the environmental impact of single-use plastic items, which often end up as litter and harm ecosystems, India implemented a ban on such items in 2022. In the fiscal year 2019–2020, the country generated an estimated 34.7-lakh tonnes per annum (TPA) of PW, with Maharashtra leading at 13%, followed by Tamil Nadu and Gujarat at 12% each. To combat the environmental impact of single-use plastic items, which often end up as litter and harm ecosystems, India implemented a ban on such items in 2022. Additionally, India mandates a system of marking or labeling on plastic carry bags and multi-layered packaging, which has been adhered to by 14 States/Union Territories (UTs). However, 25 States/UTs have reported cases of non-compliance, resulting in fines, legal action, closure orders, and the seizure of banned plastic materials.[19]

IMPACT OF PLASTICS ON CLIMATE, ENVIRONMENT AND HUMAN

Plastics, derived from fossil fuels, contribute significantly to environmental damage through the release of GHGs at various stages of their lifecycle, thereby exacerbating global warming [20]. Projections suggest that by 2050, the substantial production of plastics could account for as much as 13% of the world's carbon budget, further straining our already depleted carbon resources and perpetuating a concerning feedback loop.[21] Concerns regarding the toxicity of plastics to marine life, eventually affecting human health on entering the food chain are raised by the yearly inflow of atleast 8 million tons of scrap plastic into ocean. Inadequate management of PW results in its accumulation on riverbanks, coastlines, and landscapes, leading to increased emissions of GHGs into the atmosphere. Furthermore, the perseverance of MP poses a considerable threat to delicate ecosystems, characterized by diverse but genetically limited life forms, rendering them chiefly susceptible to the effects of climate change.[22]

On climate and environment

Over the past six decades, the prominence of plastics and its products, primarily derived from crude oil, has surged, driven by ongoing technological advancements, cost-effectiveness, and unmatched utility features. Regardless of their production method, the majority of PW ends up being either incinerated, deposited in landfills, littered, or recycled post-use, gradually emitting carbon or methane (CH_4) emissions over time.[23] Consequently, it is not astonishing that researchers project a depletion of fish populations by 2050 due to the prevalence of plastics in oceans. An estimated annual 13 million tons of the 500 billion plastic bags discarded, mostly ending up on shorelines, have led to the deaths of over 100,000 marine organisms.[24] Plastics are degraded on the surface of the ocean releasing GHG like ethylene and CH_4**.** The escalating global population exacerbates the accumulation of PW, further polluting the environment, evidenced by dwindling natural habitats, increased mortality among aquatic species, and the obstruction of sewage systems.[25] PW interferes with organic phosphorus and nitrogen, diminishing their efficacy in humus. Furthermore, Plant root cell walls experience reduced nutrient and water absorption because PW obstructs their pores within soil. The semi-permanent persistence of plastics in aquatic ecosystems exacerbates marine pollution, posing risks to aquatic organisms.[26] A substantial quantity of PW has been indiscriminately disposed of across the globe, exacerbating the ongoing issue of "white pollution." This phenomenon, stemming from the abandonment of PVC, PP, PS, and other high-molecular-weight polymers in various forms such as disposable tableware, packaging bags, plastic bottles, and agricultural mulch films, has led to environmental contamination.[27] Statistics indicate a significant increase in global plastic production over recent years. For instance, in 2015 alone, 322 million tons of plastics were manufactured worldwide, representing a 40% surge compared to production levels five years prior. This surge continued, with global production reaching 385 million tons by 2018, marking a notable increase from the 359 million tons consumed previously.[1] The trajectory of plastic production has been remarkable, intensifying from 2 million MT in 1950 to a staggering 322 million MT in 2015, outpacing the growth rate of nearly all other materials. By 2017, the cumulative global PW generated had reached a staggering 8.3 billion MT.

The burning of plastics in open air is an added threat to the white silent pandemic. Burning of plastic waste openly is defined as burning of white polymers in open fires without managing emission of toxic gases and byproducts produced. The byproducts include ashes, gases, that ultimately pollute not only air but also soil, that eventually enters into human system through food chain.[28] The plastic waste growth is exponential, alongwith its production and a never ending conversion to burned ash. A remarkable source of air pollution, open plastic burning has adverse effects on the environemnt. In one study *Reyna et.al* reported 90% emission of black carbon from PET and PS.[29] Uncovered burning of ash pollutes the groundwater, food chain and the soil. Plastic packaging making up around 40% of all the plastics produced globally includes coating and adhesives alongwith additional ingredients including fillers, plasticizers, flame retardants, colorants, stabilizers, lubricants, foaming agents and antistatic agents.[30] Particluar hazaradous additivies contains metals namely cadmium, chromium, lead, mercury, cobalt, tin and zinc.[30]

On human health

While plastic polymers themselves are generally non-toxic, but they still pose risks to society due to presence of various additives and residual monomers .These additives, which include endocrine disruptors and carcinogens, can pose health risks to humans primarily through skin contact, ingestion, and inhalation (Figure 1).[22]

Humans through food products, and air inevitably ingest MPs, which are pervasive environmental contaminants. Particle toxicity in biological systems occurs due to exposure to MPs, causing oxidative stress, inflammatory responses, and abnormal chromosome rearrangements, potentially increasing the risk of chronic inflammation and neoplasia. Ingestion is the primary route to MPs contamination in humans, with estimated intake levels ranging from 39,000 to 52,000 particles per person per year.[31] MPs can act as toxicants in various marine and freshwater organisms, intercalating in the food chain and leading to various health issues. Animals exposed MPs can pose risks to humans if consumed, as evidenced by biomonitoring studies that have identified plastic components in human tissues. Animals are frequently exposed to PW on land and in water while feeding, sometimes resulting in their death.[32] PW in aquatic environments, with its hydrophilic and high charge characteristics, can attract microorganisms that convert it into MPs. Bacteria accumulating on PW may form micro colonies, posing harm to aquatic organisms. It is also reported that gastrointestinal system absorbs MPs from contaminated food sources or breathing in polluted air which triggers inflammation alongside composition and metabolic changes in gut.[33] While dermal interaction with MPs is considered less critical, these particles are now recognized as potentially hazardous depending on susceptibility and exposure levels, contrary to their previous classification as inert particles without toxicity.[34]

The practice of open plastic burning elevates the risk of coronary heart disease while presenting dangers to breathing health and brain disorders as well as gastrointestinal distress, skin inflammation hand inefficiency, and upper body symptoms like pain and confusion. Studies show the cancer-causing pollutant group known

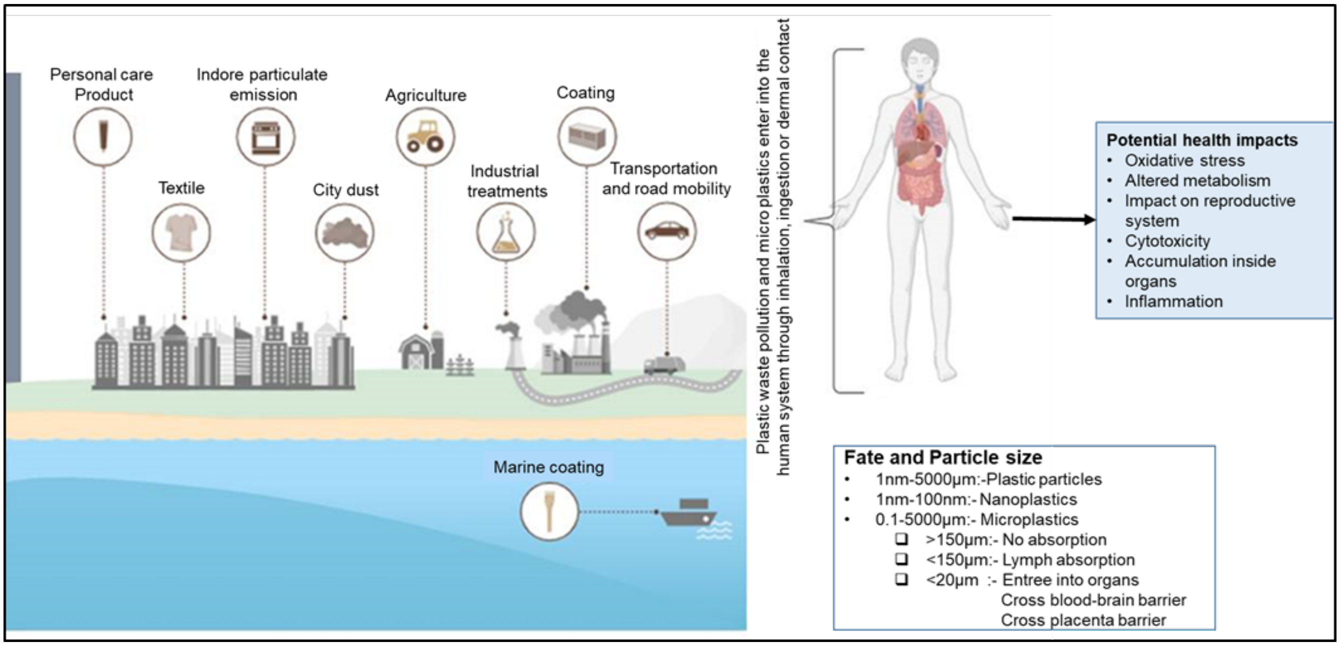


Figure 1: Effect of plastic waste and micro plastic on human health

as polycyclic aromatic hydrocarbons links directly to birth abnormalities and cancer formation.[28] Burning of PVC releases halogens into the atmosphere, producing dioxins or toxic substances. PS is a toxic polymer that harms the central nervous system (CNS). Burning of plastic exacerbates respiratory conditions like emphysema and asthma thereby resulting in rashes, headaches, nausea, and kidney damage. PS pollution is also related to damage to the reproductive and development system. Dioxins produced as a result of plastic burning settle on crops as well as waterways eventually entering the food chain.[35]

Alternate fuel in the automobile and aviation industry

PW has become a critical ecological issue, with significant quantities accumulating in landfills, oceans, and ecosystems worldwide. Innovative solutions are urgently required to address this problem and minimize its environmental consequences. One promising strategy involves converting PW into alternate fuels, offering a dual advantage of waste management and renewable energy generation.[1] In automobile transportation, a range of alternative fuels has been adopted, such as alcohol, natural gas, and biodiesel. Most internal combustion motors run on alcohol through blending it with diesel or biodiesel. The available accessibility of natural gas presents an important factor for judging its potential suitability in different applications.[36,37] Nevertheless, a homogeneous combination between natural gas and air results in a combustion mixture which produces reduced emissions than diesel engine.[38] In recent years, the automotive industry has been actively exploring alternative fuel options to reduce its dependence on fossil fuels and mitigate carbon emissions. Among these alternatives, alternate fuels derived from renewable sources have emerged as sustainable choices for powering vehicles. Now, the concept of utilizing PW to produce alternate fuels is gaining attention as a novel approach to tackling both plastic pollution and the need for cleaner fuels in the automotive sector.[39]

Furthermore, the aviation sector demands fuels tailored to its operations at high altitudes and in cold environments, characterized by low cloud and pour points and a low freezing point, among other features. Considering various factors such as energy efficiency, cost, and operational needs, biodiesel emerges as a prime candidate to meet these criteria. Commercially viable biodiesels exist as methylation products and esterification derivatives obtained from edible and non-edible vegetable oils and surplus animal fats [38]. Recently, there has been growing pressure on the aviation sector to diminish its carbon emissions and minimize its ecological footprint. Given its status as one of the most carbon-intensive forms of transport, aviation is under scrutiny for its impact on climate change. Consequently, airlines and aircraft manufacturers are proactively investigating alternative fuels sourced from renewable origins.[40] Among these substitutes, alternative fuels have attracted considerable interest due to their ability to lower GHGs emissions and advance sustainability within aviation. Presently, the idea of plastic-derived alternative fuels is emerging as an innovative remedy to confront both plastic pollution and the aviation industry's requirement for sustainable fuel alternatives.[41]

Plastic waste to alternative fuel production

The conversion of PW into alternate fuel offers a promising solution for waste management and energy production.[42] The conversion of PW into alternate fuel is highly encouraging for both waste management and energy production. Heating plastic in a low-oxygen environment to make pyrolysis oil is known as pyrolysis, while the breaking up of long polymer chains to simpler molecules is called depolymerization. Pyrolysis of PWs results in the delivery of synthetic gas, which can be processed into alternate fuels. The benefits of converting PW into alternate fuels include waste management, renewable energy, resource recovery, and economic opportunities.[43] However, challenges like technological limitations and ensuring sustainability require attention for extensive adoption of plastic-to-alternate fuel processes. Additionally, environmental and social impacts must be carefully considered to ensure sustainability and social responsibility. Different protocols involved in alternate fuel production from PW are discussed below:

Pyrolysis/Thermal Degradation:

It involves a sophisticated sequence of chemical and thermal reactions that break down organic materials, such as plastic, without the presence of oxygen.[44] The procedure involves heating plastics to elevated temperature, followed by the distillation or separation of volatile substances for repurposing as an energy source.[45] During the pyrolysis of waste plastic, the material undergoes exposure to high temperatures without oxygen, often aided by a catalyst to facilitate the moderate breaking of molecular chains. Subsequently, the gases generated are condensed in a condenser to obtain waste plastic oil with low sulfur content.[46] Thermal decomposition of plastics breaks down the three primary fractions of plastics, namely gas, crude oil, and solid residue. Higher boiling point hydro-carbon (HC) from non-catalytic pyrolysis make up the crude oil.[47] Optimizing variables, including catalysts, pyrolysis temperature, and plastic-to-catalyst ratios is essential for the efficient manufacture of gasoline and diesel from PW. The combination of polymers with coal and shale oil through co-pyrolysis leads to better crude oil quality by decreasing its viscosity.[48] By thermal breakdown of long-chain polymers into shorter, simpler molecules in the absence of oxygen, pyrolysis turns PW into solid, liquid, or gaseous fuels. Carbonized char, flammable oils, and combustible gases with high calorific value are the main byproducts of pyrolysis.[49] Pyrolysis involves breaking down a material through heat without oxygen. Plastic is inserted into a cylindrical chamber where it undergoes this process. The resulting gases are cooled and condensed in a unique condenser setup, resulting in a hydrocarbon mixture containing various types of HC.[48] These HC are then separated into liquid fuel products through fractional distillation. The plastic is subjected to pyrolysis within a temperature range of 370°C to 420°C.[50]

The key stages of plastic pyrolysis include (Figure 2):

- Uniformly heating the plastic within a specific temperature range to avoid significant temperature fluctuations.
- Removing oxygen from the pyrolysis chamber.
- Controlling the formation of carbonaceous char residue thus preventing from becoming a thermal obstacle and decreasing transmission of heat to the plastic.
- Precisely condensing and separating the pyrolysis vapours to obtain a high-quality and consistent distillate

Through pyrolysis, waste plastics are transformed into an alternate energy source suitable for automobile and aviation industries. The characteristics of this waste plastic fuel fluctuate depending on the type of plastics used and the pyrolysis method applied [51]. Despite its potential as a fuel, waste plastic fuel faces significant drawbacks such as low calorific value and high viscosity when compared to traditional diesel fuel. High-density polyethylene (HDPE) has exceptional endurance due to its linear long-chain polymer structure, which is characterized by high crystallinity and low branching. [52]. However, the soaring global demand for HDPE, projected to hit approximately 95 billion tons by 2025, contributes significantly to white pollution. Nevertheless, HDPE boasts resistance to alkalis, weak acids, and greases, making it a preferred choice for manufacturing various products like milk containers, shampoo bottles, and recycling bins [53]. HDPE waste holds promise as a valuable feedstock for pyrolysis, offering multiple recycling opportunities. Researchers like Ning Liu et al. have explored methods to recover energy from waste polymers for solar energy applications, highlighting its environmental friendly and economically viable potential. By converting low-cost waste polymers into porous carbons, this approach presents a sustainable pathway for high-value energy utilization across diverse applications.[54,55]

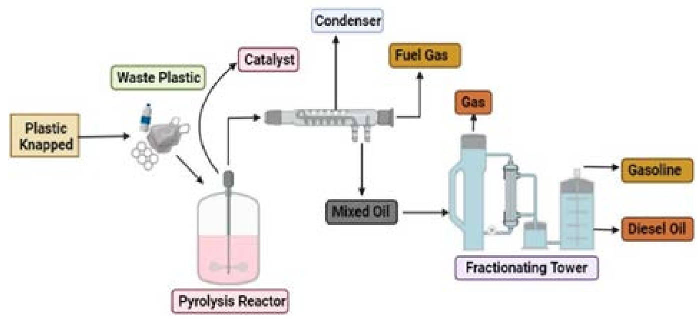


Figure 2. Stages of pyrolysis

Depolymerisation:

In this technique, plastics for alternative fule production entails the conversion of the lengthy polymer chains found in plastics into smaller hydro-carbon molecules suitable for use as fuels. Various techniques can accomplish this, such as pyrolysis, catalytic depolymerisation, and thermal depolymerisation (Figure 3).

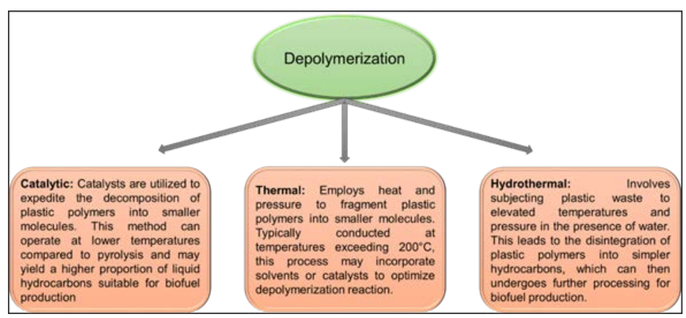


Figure 3: Types of depolymerization

Catalytic Degradation:

In this technique, an appropriate catalyst is employed to initiate the cracking reaction, leading to a reduction in both reaction temperature and duration. Consequently, the process yields a narrower range of carbon atom numbers in the products, with a peak in lighter HC occurring at lower degrees. Economically, catalytic pyrolysis is appealing since it is less expensive. The goal of catalytic pyrolysis optimization is to use as little catalyst as possible by reusing and using small amounts of catalysts. Cost-effectiveness, reduced pollution from PW, and fewer solid leftovers are some advantages of catalytic pyrolysis.[56,57] In catalytic-cracking pyrolysis, the polymeric material is heated in an inert atmosphere while catalysts are present. Catalytic cracking occurs between 350°C and 550°C. Either pure or mixed plastics can be recycled using this method. In comparision to thermal pyrolysis, it produces fuel oils of superior quality.[49] The catalyst facilitates low-temperature, low-energy breakdown processes, which lowers expenses, speeds up cracking reactions, improves process selectivity, and increases the yield of high-value products.[58] The waste plastic enters a cracking vessel containing two heating systems. The base of the vessel uses a primary heating element while the top surface has a secondary heating component. A cracked oil by-product is produced when the cracked gas evaporated in the cracking vessel is cooled in a cooling vessel.[59]

Gasification:

Method of chemically and thermally converting carbon-based materials into predominantly gaseous products using a gasification agent, typically air, oxygen, or steam. When preceded by pyrolysis, gasification can enhance the outputs of pyrolysis, such as gas, tar, and char, by partially oxidizing the more complex HC, predominantly those present in the char and tar fractions.[60–62] This process utilizes carbon dioxide (CO_2), steam, limited amounts of air or oxygen (O_2), or combinations thereof to produce synthesis gas (syngas).[63] The products of gasification typically include solids, liquids, and gases. Liquid products, such as oil and tar, are present in smaller amounts, approximately 10–20% by weight of the input, under certain conditions. Gas yield, by weight of the feedstock, can range from 30 to 60.[64,65] Plastics gasification seeks to achieve maximum conversion into a syngas or gaseous product, minimizing the production of unwanted by-products such as char and tar.[66] Gasification is a multi-faceted process involving numerous chemical reactions described below. Initially, in the drying phase, moisture within the feedstock transforms into steam at (20 to 100°C), with no chemical reactions occurring at this stage. However, the feedstock typically retains a moisture content of 10 to 20%. Subsequently, during pyrolysis, the dry feedstock undergoes thermal degradation between 150 and 700°C in the absence of oxygen, yielding volatile elements and the formation of ash and char residue. The volatiles emitted en-compass hydrogen, CO_2, tar, CO, water vapor, and light HC. Following pyrolysis, oxidation reactions occur, generating the requisite heat for endothermic processes.[62,63,67] CO_2 is generated through the interaction of oxygen with char, while hydrogen in the feedstock undergoes oxidation to produce water. Despite sub-stoichiometric oxygen levels, partial oxidation of carbon leads to carbon monoxide production. Lastly, in the reduction phase, occurring without oxygen, various chemical reactions, primarily endothermic, arise due to oxygen consumption in earlier oxidation stages.[68] Key products of reduction include methane, carbon monoxide, and hydrogen. Gasifying PP and PE results in syngas with hydrogen concentrations of up to 40%, corresponding to production rates of 4–3 wt% of H_2 per 100 g of plastic. Nevertheless, the significant feature of the gas composition is the elevated levels of CH_4 (40% and 30%, respectively) and ethylene (11% and 15%) in the PP and PE gasification processes.[69,70] This leads to a high heating value of up to 25 MJ/m^3 due to the abundant presence of HC. Nonetheless, the considerable concentrations of light HC and CH_4, as observed by previous researchers, suggest the presence of tar. In both plastics, tar content exceeds 120 g/m^3, with naphthalene being the predominant compound.[71] Various types of reactor used for different PW are listed in Table 1.

PRODUCTION OF A FUEL USING BIOMASS AND GENETIC ENGINEERING FROM MICROBES

Industrial applications of fossil fuel include both energy production as well as transportation fuel and biomaterial synthesis. Use of fossil fuel in industrial and automobile industries are a major source of pollution, hence switching to alternate fuel results in substantial decrease of GHG emission. The process breaks downs plant materials to separate fermentable sugars which microbial transformations convert into alternative fuel [77]. Morever, alternate fuel crops with high yeilds help decrease in both competitionfor food-growing lands and losses to biodiversity conservation.

Table 1:Different reactor for gasification of different plastics

Type of plastic	Reactor	Reference
Waste plastic	Plasma reactor	72
PE	Spouted bed reactor and packed bed reactor	73
PET	Semi batch and fixed bed reactor	74
PS+PE PET+PE PP PE	Fluidized bed	75
HDPE PS PP PW PW and refuse paper	Fixed batch	76

Agricultural biomass fibres represented by palm kernel shell (PKS) demonstrate strong potential to boost biodiesel production hence promoting sustainability goals [78]. Chemical processes discussed above are used for plastic conversion to alternate fuel, notably algae and engineered microorganisms are also studied for effective production of plastic-derived alternate fuels.

Since alternate fuels like bioethanol, biodiesel and biohydrogen are promising substitute for fossil fuels, algal biomass is an encourging raw material for its production. It requires minimal processing and doesnot interefre with the cultivation of food crops. Additionally, microalgae are mixotrophic, making then well-suited for energy and alternate fuel production.[79] Photosynthetic organisms that inclde plants, algae and some bacteria are of interest in alternate fuel production due to their low requirements than their autotrophic counterparts. Plant derived biofuels struggle to compete with agricultural needs for cropland resiurces and experience restricted harvesting opportunities which coinstrain their production.The biomass growth rates for algae are superior to that of plant, avoiding all challenges faced by plants.[79] Macro-and micro algae referred to as thrid generation biomass offers numerous advantages like fast growing, efficient removal of carbon-dioxide and can synthesize polysaccharides or oil for alternate fuel production.[80,81] In a review Bhaskar et. al reported that many algae has the capacity to convert biomass to biodiseal as for example red algae (*Chondrus ocellatus*, *Porphyra perforate*, *Gloiopeltis fenax*, *Gracilaria crassa*), brown algae (*Hedophyllum sessile*, *Saccharina japonica*, *Nereocystis luetkeana*), green algae (*Caulerpa scalpelliformis*, *Ulva fenestrate*, *Chaetomorpha linum*).[82]

Genetic engineering has improved microbes' ability to degrade plastic waste into alternate fuel production. Researchers have modified bacterial strains for enhancing th efficacy in breakdown various plastic polymers. Studies reflect gene editing and metabolic engineering increase bacteria's hydrolytic activity towards different plastic types, facilitating more effective biodegradation strategies.[83] PET for example a plastic polymer can be degraded via hydrolysis; with depolymerization as step 1 followed by degradation to its monomeric units mono(2-hydroxyethyl) terephthalate (MHET) and BHET, yeilding TPA and glycerol. Although PETase enzyme facilitate the degradation of PET to MHET and TPA, some PETase enzymes fails to carry out both the steps. This can be carried out with the help of enzymes secreted by certain bacteria like PE-H (*Pseudomonas aestusnigri*) and IsPETase (*Ideonella sakaiensis*).[84,85] Kawai et.al reported a triple mutagenesis of CUT190 to Ser226Pro/Arg228Ser/Thr262Lys from *Saccharomonospora viridis* AHK190 resulted in higher efficiency of enzymatic activity and thermostability thereby imparting faster degradation rate.[83] Another study by Sulaiman et.al[86] reports cloning of leaf-branch compost cutinase with highest idnetity with *Thermomonospora curvata* (*T.curvata)* lipase accelerated the degradation rate by 59.7% under specific conditions at a rate if 12mg/h.mg of the enzyme than compared to *T. fusca* cutinase at specified conditions at a rate of 0.05mg/h/mg of the enzyme.[87]

Discussion and future prospects

Plastic waste accumulation today creates large environmental problems because plastic remains in nature indefinitely and the standard waste removal methods prove unsatisfactory. The current recycling methods using mechanical and chemical procedures need improved options because their economic performance remains low.[88] Bioenergy emerges as a remedial approach since its conversion to disposed plastics both eliminates plastic waste-producing problems while creating renewable energy supplies.[89] Thermochemical processes including pyrolysis, gasification and hydrothermal liquefaction (HTL) show exceptional efficiency when turning plastic waste into alternative fuels.[90] The pyrolysis process creates extractable pyrolysis oil that becomes conventional fuels after refinement and gasification produces usable syngas fuel. The high-pressure water application in HTL creates bio-crude oil from plastics that enterprises can refine into valuable hydrocarbon products.[91] The effectiveness of converting plastic waste to valuable products through these methods depends on extensive energy requirements that challenge sustainability standards until renewable power becomes involved. Although biological conversion techniques provide sustainable plastic decomposition through the use of microbial organisms together with enzymatic resources. Random microorganisms including *Ideonella sakaiensis* and *Pseudomonas putida* demonstrate metabolic capabilities that transform PET and PU plastics into alternate fuel precursor products such as ethanol or butanol and polyhydroxyalkanoates (PHAs).[92] Enzyme-based degradation technologies that use PETase along with MHETase demonstrate promising abilities to degrade PET plastics more efficiently yet face obstacles in achieving industrial scale implementation.[93] Research in synthetic biology together with enzyme engineering technology and microbial consortia optimization promises to boost the efficiency and practical implementation of biological plastic-to-alternate fuel transformation processes. Experimental analyses show thermochemical practices provide short-term operational capabilities yet biological transformations demonstrate future potential through their lower impact on the environment. The future of plastic waste-to-alternate energy innovation requires researchers to develop amalgamated process integration and create policy initiatives which stimulate sustainable plastic conversion initiatives. The combination of different strategies provides a pathway to turn plastic waste from environmental peril into valuable material which generates electricity.

Conclusion

Alternate fuel production from plastic waste PW provides a long-term answer to energy and environmental problem. PW serves as a renewable energy sources and reduces pollution and trash by keping it out of landfills and the water. PW-sourced alternate fuels increase energy security and lessen dependency on limited fossil fuels. Because of similar carbon footprints they also help fight climate change by lowering GHG emissions. Converting PW into alternate fuel supports the circular economy's tenets of employment development and resource conservation. PW conversion into alternate fuels have both beneficial and detrimental effects on the environemnt. Positively, it lessens littereing and garbage volumes, thereby benefitting ecosystem and animals. It also supports the ideas of circular economy and helps conserev resources. However emissions and contaminants may be produced during the conversion process, particularly during insufficient measures of pollution control. Aditionally, if used improperly, chemical catalysts or solvents in depolymerization processes can be hazardous to both human and environment.

Degradation of macroplastics produces microplastics that penetrate into the food chain hence potentially making its way into human body where they are deposited over years. The human body encounters solemn health risks because of white polymer particles combined with harmful chemicals that when leaked has been proven to cause severe endocrine disruption and developmental disorders in addition to respiratory complications and cancer.

The advancement of a cleaner sustainable environment depends heavily on widespread public awareness and joint community effort against plastic hazards. Motivated work to fight against plastic pollution permits to minimize its destructive impact on human health while safe-guarding Earth's life-supporting environmental systems.

Acknowledgments

The authors acknowledge Uttaranchal University and Kristu Jayanti College for providing the opportunity and facilities for the study. K.A. is thankful to Wellcome Trust/DBT India Alliance.

Conflict of Interest Statement

The authors declare that no competing interests exist

REFERENCES AND NOTES

1. R. Kumar, A. Verma, A. Shome, et al. Impacts of Plastic Pollution on Ecosystem Services, Sustainable Development Goals, and Need to Focus on Circular Economy and Policy Interventions. *Sustain. 2021, Vol. 13, Page 9963* **2021**, 13 (17), 9963.
2. L.G. Nair, K. Agrawal, P. Verma. An overview of sustainable approaches for bioenergy production from agro-industrial wastes. *Energy Nexus* **2022**, 6 (April), 100086.
3. A.S. Jatoi, J. Ahmed, N.M. Mubarak, et al. A Comprehensive Review on Handling of Plastic Waste For Energy Generation—Current Status and Future Challenges. *Water. Air. Soil Pollut.* **2023**, 234 (12), 1–29.
4. M. Shams, I. Alam, M.S. Mahbub. Plastic pollution during COVID-19: Plastic waste directives and its long-term impact on the environment. *Environ. Adv.* **2021**, 5, 100119.
5. O. Kehinde, O.J. Ramonu, K.O. Babaremu, L.D. Justin. Plastic wastes: environmental hazard and instrument for wealth creation in Nigeria. *Heliyon* **2020**, 6 (10), e05131.
6. S. Huang, H. Wang, W. Ahmad, et al. Plastic Waste Management Strategies and Their Environmental Aspects: A Scientometric Analysis and Comprehensive Review. *Int. J. Environ. Res. Public Health* **2022**, 19 (8).
7. H.K. Webb, J. Arnott, R.J. Crawford, E.P. Ivanova. Plastic Degradation and Its Environmental Implications with Special Reference to Poly(ethylene terephthalate). *Polym. 2013, Vol. 5, Pages 1-18* **2012**, 5 (1), 1–18.
8. S.Y. Lee, R. Sankaran, K.W. Chew, et al. Waste to bioenergy: a review on the recent conversion technologies. *BMC Energy 2019 11* **2019**, 1 (1), 1–22.
9. M. Chandran, S. Tamilkolundu, C. Murugesan. Conversion of plastic waste to fuel. *Plast. Waste Recycl.* **2020**, 385–399.
10. M. Kiehbadroudinezhad, A. Merabet, C. Ghenai, A.G. Abo-Khalil, T. Salameh. The role of biofuels for sustainable MicrogridsF: A path towards carbon neutrality and the green economy. *Heliyon* **2023**, 9 (2).
11. A.G. Adeniyi, K.O. Iwuozor, E.C. Emenike, et al. Thermochemical co-conversion of biomass-plastic waste to biochar: a review. *Green Chem. Eng.* **2024**, 5 (1), 31–49.
12. H. Durak. Comprehensive Assessment of Thermochemical Processes for Sustainable Waste Management and Resource Recovery. *Process. 2023, Vol. 11, Page 2092* **2023**, 11 (7), 2092.
13. A.K. Rana, M.K. Thakur, A.K. Saini, et al. Recent developments in microbial degradation of polypropylene: Integrated approaches towards a sustainable environment. *Sci. Total Environ.* **2022**, 826, 154056.
14. T.D. Moshood, G. Nawanir, F. Mahmud, et al. Sustainability of biodegradable plastics: New problem or solution to solve the global plastic pollution? *Curr. Res. Green Sustain. Chem.* **2022**, 5, 100273.
15. J.Y. Boey, C.K. Lee, G.S. Tay. Factors Affecting Mechanical Properties of Reinforced Bioplastics: A Review. *Polym. 2022, Vol. 14, Page 3737* **2022**, 14 (18), 3737.
16. U. Kong, N.F. Mohammad Rawi, G.S. Tay. The Potential Applications of Reinforced Bioplastics in Various Industries: A Review. *Polym. 2023, Vol. 15, Page 2399* **2023**, 15 (10), 2399.
17. I. Fahim, O. Mohsen, D. Elkayaly. Production of Fuel from Plastic Waste: A Feasible Business. *Polymers (Basel).* **2021**, 13 (6).
18. H. Alexander, B. Adly, Y. Khalil, et al. Strengthening Entrepreneurship and Enterprise Development. **2018**, No. Year 4, 231.
19. Towards a Circular Plastics Economy: India's Actions to #BeatPlasticPollution | TERI https://www.teriin.org/article/towards-circular-plastics-economy-indias-actions-beatplasticpollution (accessed Feb 26, 2024).
20. H. V. Ford, N.H. Jones, A.J. Davies, et al. The fundamental links between climate change and marine plastic pollution. *Sci. Total Environ.* **2022**, 806, 150392.
21. S. Sharma, V. Sharma, S. Chatterjee. Contribution of plastic and microplastic to global climate change and their conjoining impacts on the environment - A review. *Sci. Total Environ.* **2023**, 875.
22. Z. Yuan, R. Nag, E. Cummins. Human health concerns regarding microplastics in the aquatic environment - From marine to food systems. *Sci. Total Environ.* **2022**, 823, 153730.
23. R. Andreazza, K. Keneuwe Khoaele, O. Joseph Gbadeyan, V. Chunilall, B. Sithole. The Devastation of Waste Plastic on the Environment and Remediation Processes: A Critical Review. *Sustain. 2023, Vol. 15, Page 5233* **2023**, 15 (6), 5233.
24. E. Fournier, L. Etienne-Mesmin, C. Grootaert, et al. Microplastics in the human digestive environment: A focus on the potential and challenges facing in vitro gut model development. *J. Hazard. Mater.* **2021**, 415.
25. J. Oliveira, A. Belchior, V.D. da Silva, et al. Marine Environmental Plastic Pollution: Mitigation by Microorganism Degradation and Recycling Valorization. *Front. Mar. Sci.* **2020**, 7, 567126.
26. J.Y. Uwamungu, Y. Wang, G. Shi, et al. Microplastic contamination in soil agro-ecosystems: A review. *Environ. Adv.* **2022**, 9, 100273.
27. G. Maitlo, I. Ali, H.A. Maitlo, et al. Plastic Waste Recycling, Applications, and Future Prospects for a Sustainable Environment. *Sustain. 2022, Vol. 14, Page 11637* **2022**, 14 (18), 11637.
28. G. Pathak, M. Nichter, A. Hardon, et al. Plastic pollution and the open burning of plastic wastes. *Glob. Environ. Chang.* **2023**, 80 (August 2022), 102648.
29. N. Reyna-Bensusan, D.C. Wilson, S.R. Smith. Uncontrolled burning of solid waste by households in Mexico is a significant contributor to climate change in the country. *Environ. Res.* **2018**, 163, 280–288.
30. K.J. Groh, T. Backhaus, B. Carney-Almroth, et al. Overview of known plastic packaging-associated chemicals and their hazards. *Sci. Total Environ.* **2019**, 651, 3253–3268.
31. K.H.D. Tang, R. Li, Z. Li, D. Wang. Health risk of human exposure to microplastics: a review. *Environ. Chem. Lett. 2024 223* **2024**, 22 (3), 1155–1183.
32. A. Ratnasari, I.F. Zainiyah, T. Hadibarata, et al. The Crucial Nexus of Microplastics on Ecosystem and Climate Change: Types, Source, Impacts, and Transport. *Water. Air. Soil Pollut.* **2024**, 235 (5), 1–18.
33. M.N. Issac, B. Kandasubramanian. Effect of microplastics in water and aquatic systems. *Environ. Sci. Pollut. Res. 2021 2816* **2021**, 28 (16), 19544–19562.
34. J.C. Prata, J.P. da Costa, I. Lopes, A.C. Duarte, T. Rocha-Santos. Environmental exposure to microplastics: An overview on possible human health effects. *Sci. Total Environ.* **2020**, 702, 134455.
35. R. Verma, K.S. Vinoda, M. Papireddy, A.N.S. Gowda. Toxic Pollutants from Plastic Waste- A Review. *Procedia Environ. Sci.* **2016**, 35, 701–708.
36. Deepshika, K. Chauhan. Chemo-enzymatic conversion of biomass into bio-ethanol. *J. Integr. Sci. Technol.* **2014**, 2 (1), 34–36.
37. M. Deshmukh, A. Pande. Effects of blending bioethanol with gasoline on spark–ignition engine – A review. *J. Integr. Sci. Technol.* **2022**, 10 (2), 87–99.
38. S. Das, A. Chowdhury. An exploration of biodiesel for application in aviation and automobile sector. *Energy Nexus* **2023**, 10, 100204.
39. C. Bae, J. Kim. Alternative fuels for internal combustion engines. *Proc. Combust. Inst.* **2017**, 36 (3), 3389–3413.
40. A.H. Pescador. Reducing the Carbon Footprint of Aviation while Increasing Profitability of International Airlines. **2020**, No. August.
41. Y. Liu, P. Cruz-Morales, A. Zargar, et al. Biofuels for a sustainable future. *Cell* **2021**, 184 (6), 1636–1647.
42. A.F.J. Tan, S. Yu, C. Wang, et al. Reimagining plastics waste as energy solutions: challenges and opportunities. *npj Mater. Sustain. 2024 21* **2024**, 2 (1), 1–7.
43. T. Xayachak, N. Haque, R. Parthasarathy, et al. Pyrolysis for plastic waste management: An engineering perspective. *J. Environ. Chem. Eng.* **2022**, 10 (6), 108865.
44. M.J.B. Kabeyi, O.A. Olanrewaju. Design and modelling of a waste heat recovery system for a 250kw diesel engine for process heating in the energy transition. *Proc. Int. Conf. Ind. Eng. Oper. Manag.* **2020**, 59 (February), 119–129.
45. M. Jeremiah, B. Kabeyi, O.A. Olanrewaju. Diesel to Gas Engine Power Plant Conversion: A Review and Preliminary Design for an Operating Power Plant. *Res. Artic. J. Energy Manag. Technol.* **2023**, 7, 3.
46. W. Bekele, W. Amedie, Z. Salehudres. Design of Pyrolysis Reactor for Waste Plastic Recycling. *Eng. Appl. Sci.* **2020**, 5 (5), 92.
47. F. Faisal, M.G. Rasul, M.I. Jahirul, A.A. Chowdhury. Waste plastics pyrolytic oil is a source of diesel fuel: A recent review on diesel engine

performance, emissions, and combustion characteristics. *Sci. Total Environ.* **2023**, 886, 163756.
48. B. Kunwar, H.N. Cheng, S.R. Chandrashekaran, B.K. Sharma. Plastics to fuel: a review. *Renew. Sustain. Energy Rev.* **2016**, 54, 421–428.
49. M.J.B. Kabeyi, O.A. Olanrewaju. Review and Design Overview of Plastic Waste-to-Pyrolysis Oil Conversion with Implications on the Energy Transition. *J. Energy* **2023**, 2023, 1–25.
50. Motawie, Ibrahim, Ahmed, Sahar Ahmed, Abualsoud. Fractional Distillation of Fuel From Mixed Plastic Wast. *Researchgate* **2016**, No. December 2016, 1–9.
51. N.K. Ndiaye, N.S.A. Derkyi, E. Amankwah. Pyrolysis of plastic waste into diesel engine-grade oil. *Sci. African* **2023**, 21, e01836.
52. M.Z.H. Khan, M. Sultana, M.R. Al-Mamun, M.R. Hasan. Pyrolytic Waste Plastic Oil and Its Diesel Blend: Fuel Characterization. *J. Environ. Public Health* **2016**, 2016.
53. S. Padmanabhan, K. Giridharan, B. Stalin, et al. Energy recovery of waste plastics into diesel fuel with ethanol and ethoxy ethyl acetate additives on circular economy strategy. *Sci. Reports 2022 121* **2022**, 12 (1), 1–13.
54. N. Liu, L. Hao, B. Zhang, et al. Rational Design of High-Performance Bilayer Solar Evaporator by Using Waste Polyester-Derived Porous Carbon-Coated Wood. *Energy Environ. Mater.* **2022**, 5 (2), 617–626.
55. N. Liu, Z. Hu, L. Hao, et al. Trash into treasure: Converting waste polyester into C3N4-based intramolecular donor-acceptor conjugated copolymer for efficient visible-light photocatalysis. *J. Environ. Chem. Eng.* **2022**, 10 (1), 106959.
56. G.G.N. Thushari, J.D.M. Senevirathna. Plastic pollution in the marine environment. *Heliyon* **2020**, 6 (8), e04709.
57. M.J.B. Kabeyi, O.A. Olanrewaju. Fuel from plastic wastes for sustainable energy transition. *Proc. Int. Conf. Ind. Eng. Oper. Manag.* **2021**, No. July, 1023–1034.
58. S.M. Al-Salem, A. Antelava, A. Constantinou, G. Manos, A. Dutta. A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). *J. Environ. Manage.* **2017**, 197, 177–198.
59. J.P. Lange. Managing Plastic Waste-Sorting, Recycling, Disposal, and Product Redesign. *ACS Sustain. Chem. Eng.* **2021**, 9 (47), 15722–15738.
60. R.C. Brown. The Role of Pyrolysis and Gasification in a Carbon Negative Economy. *Process. 2021, Vol. 9, Page 882* **2021**, 9 (5), 882.
61. R. Rauch, Y. Kiros, K. Engvall, et al. Hydrogen from Waste Gasification. *Hydrog. 2024, Vol. 5, Pages 70-101* **2024**, 5 (1), 70–101.
62. H.H. Shah, M. Amin, A. Iqbal, et al. A review on gasification and pyrolysis of waste plastics. *Front. Chem.* **2023**, 10, 960894.
63. Y. Gao, M. Wang, A. Raheem, et al. Syngas Production from Biomass Gasification: Influences of Feedstock Properties, Reactor Type, and Reaction Parameters. *ACS Omega* **2023**, 8 (35), 31620–31631.
64. Q. Hu, W. Cheng, Q. Mao, et al. Study on the physicochemical structure and gasification reactivity of chars from pyrolysis of biomass pellets under different heating rates. *Fuel* **2022**, 314, 122789.
65. A.I. Osman, N. Mehta, A.M. Elgarahy, et al. Conversion of biomass to biofuels and life cycle assessment: a review. *Environ. Chem. Lett. 2021 196* **2021**, 19 (6), 4075–4118.
66. G. Lopez, M. Artetxe, M. Amutio, et al. Recent advances in the gasification of waste plastics. A critical overview. *Renew. Sustain. Energy Rev.* **2018**, 82, 576–596.
67. F.G. Fonseca, A. Funke, A. Niebel, A.P. Soares Dias, N. Dahmen. Moisture content as a design and operational parameter for fast pyrolysis. *J. Anal. Appl. Pyrolysis* **2019**, 139, 73–86.
68. S.R. Akkala, M. Jeremias, A.K. Kaviti, V.S. Sikarwar. Biomass conversion by gasification process. *Ref. Modul. Earth Syst. Environ. Sci.* **2023**.
69. N. Aryal, M. Odde, C. Bøgeholdt Petersen, L. Ditlev Mørck Ottosen, M. Vedel Wegener Kofoed. Methane production from syngas using a trickle-bed reactor setup. *Bioresour. Technol.* **2021**, 333, 125183.
70. J. Makwana, A.D. Dhass, P. V. Ramana, D. Sapariya, D. Patel. An analysis of waste/biomass gasification producing hydrogen-rich syngas: A review. *Int. J. Thermofluids* **2023**, 20, 100492.
71. A. Jayanarasimhan, R.M. Pathak, A.M. Shivapuji, L. Rao. Tar Formation in Gasification Systems: A Holistic Review of Remediation Approaches and Removal Methods. *ACS Omega* **2023**.
72. P.G. Rutberg, V.A. Kuznetsov, E.O. Serba, et al. Novel three-phase steam-air plasma torch for gasification of high-caloric waste. *Appl. Energy* **2013**, 108, 505–514.
73. A. Erkiaga, G. Lopez, M. Amutio, J. Bilbao, M. Olazar. Syngas from steam gasification of polyethylene in a conical spouted bed reactor. *Fuel* **2013**, 109, 461–469.
74. J.W. Lee, T.U. Yu, J.W. Lee, et al. Gasification of Mixed Plastic Wastes in a Moving-Grate Gasifier and Application of the Producer Gas to a Power Generation Engine. *Energy & Fuels* **2013**, 27 (4), 2092–2098.
75. S. Martínez-Lera, J. Torrico, J. Pallarés, A. Gil. Thermal valorization of post-consumer film waste in a bubbling bed gasifier. *Waste Manag.* **2013**, 33 (7), 1640–1647.
76. P. Friengfung, E. Jamkrajang, S. Sunphorka, P. Kuchonthara, L. Mekasut. NiO/dolomite catalyzed steam/O2 gasification of different plastics and their mixtures. *Ind. Eng. Chem. Res.* **2014**, 53 (5), 1909–1915.
77. A. Furtado, J.S. Lupoi, N. V. Hoang, et al. Modifying plants for biofuel and biomaterial production. *Plant Biotechnol. J.* **2014**, 12 (9), 1246–1258.
78. M.A. Shakir, M.I. Ahmad, F.Z. Mansur, H.P.S. Abdul Khalil. Biomass to biofuel: Palm kernel shells as catalyst supports for enhanced biodiesel production. *Biofuels, Bioprod. Biorefining* **2024**, 18 (6), 2038–2052.
79. R.A. Voloshin, M. V. Rodionova, S.K. Zharmukhamedov, T. Nejat Veziroglu, S.I. Allakhverdiev. Review: Biofuel production from plant and algal biomass. *Int. J. Hydrogen Energy* **2016**, 41 (39), 17257–17273.
80. O.K. Lee, E.Y. Lee. Sustainable production of bioethanol from renewable brown algae biomass. *Biomass and Bioenergy* **2016**, 92, 70–75.
81. J. ye Lee, P. Li, J. Lee, H.J. Ryu, K.K. Oh. Ethanol production from Saccharina japonica using an optimized extremely low acid pretreatment followed by simultaneous saccharification and fermentation. *Bioresour. Technol.* **2013**, 127, 119–125.
82. G. Baskar, I.A.E. Selvakumari, R. Aiswarya. Marine Algae-Future Source of Biofuels. *Int. J. Mod. Sci. Technol.* **2018**, 3 (4), 72–82.
83. D. Martín-González, C. de la Fuente Tagarro, A. De Lucas, S. Bordel, F. Santos-Beneit. Genetic Modifications in Bacteria for the Degradation of Synthetic Polymers: A Review. *Int. J. Mol. Sci.* **2024**, 25 (10), 5536.
84. V. Tournier, S. Duquesne, F. Guillamot, et al. Enzymes' Power for Plastics Degradation. *Chem. Rev.* **2023**, 123 (9), 5612–5701.
85. T. Muringayil Joseph, S. Azat, Z. Ahmadi, et al. Polyethylene terephthalate (PET) recycling: A review. *Case Stud. Chem. Environ. Eng.* **2024**, 9, 100673.
86. S. Sulaiman, S. Yamato, E. Kanaya, et al. Isolation of a novel cutinase homolog with polyethylene terephthalate-degrading activity from leaf-branch compost by using a metagenomic approach. *Appl. Environ. Microbiol.* **2012**, 78 (5), 1556–1562.
87. R.J. Müller, H. Schrader, J. Profe, K. Dresler, W.D. Deckwer. Enzymatic Degradation of Poly(ethylene terephthalate): Rapid Hydrolyse using a Hydrolase from T. fusca. *Macromol. Rapid Commun.* **2005**, 26 (17), 1400–1405.
88. S.S.V. Vuppaladadiyam, A.K. Vuppaladadiyam, A. Sahoo, et al. Waste to energy: Trending key challenges and current technologies in waste plastic management. *Sci. Total Environ.* **2024**, 913.
89. B. Sharma, S. Shekhar, S. Sharma, P. Jain. The paradigm in conversion of plastic waste into value added materials. *Cleaner Engineering and Technology*. 2021.
90. M. Usman, S. Cheng, S. Boonyubol, J.S. Cross. From biomass to biocrude: Innovations in hydrothermal liquefaction and upgrading. *Energy Conversion and Management*. 2024.
91. N. Nkosi, E. Muzenda, J. Gorimbo, M. Belaid. Developments in waste tyre thermochemical conversion processes: gasification, pyrolysis and liquefaction. *RSC Adv.* **2021**, 11 (20), 11844–11871.
92. G.H. Lee, D.W. Kim, Y.H. Jin, et al. Biotechnological Plastic Degradation and Valorization Using Systems Metabolic Engineering. *Int. J. Mol. Sci.* **2023**, 24 (20), 15181.
93. A. Barclay, K.R. Acharya. Engineering Plastic Eating Enzymes Using Structural Biology. *Biomolecules* **2023**, 13 (9), 1407.