

Review of Conversion Technologies of Waste Polystyrene into useful Products

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Abstract: Polystyrene usage has risen significantly in recent years as a result of its wide variety of applications. The persistent consumer demand for polystyrene resulted in the accumulation of polystyrene waste in landfills, inducing environmental degradation. Since polystyrene is a petroleum-derived material, the increasing demand for it resulted in the depletion of petroleum, a non-renewable energy source. Research teams from all over the world have invented many methods for dealing with polystyrene waste, including recycling and energy regeneration. However, there are drawbacks to recycling methods, such as the fact that they need a lot of manpower in the separating procedure and pollute the water, reducing the process's sustainability. Because of these flaws, the experimenters have centered their efforts on the energy harvesting approach. As petroleum is the primary component of polystyrene, the pyrolysis process for recovering fuel oil from polystyrene is an useful technology because the retrieved oil has a higher calorific value than commercially available gasoline. The current paper discusses polystyrene conversion technologies as well as the pyrolysis techniques for polystyrene, which generates end products such as oil, gas, and char. The impact of different processing parameters on the product yield has been addressed using more advanced techniques of conducting pyrolysis with a solvent.

Keywords: Polystyrene Waste; Pyrolysis; Fuel Oils

I. INTRODUCTION

Polymer has played a critical importance in the advancement of human society for the past fifty years [1]. It has stimulated the growth of a number of industries, including packaging, electronics, cars, medical care, and construction [1]. The demand for polymer has increased as the world's population has expanded rapidly. As a result, global polymer production reached nearly 359 million tonnes in 2018 [2]. The constant rise in polymer demand resulted in an annual rise in plastics waste. According to 2013 statistics, the United States

generated nearly 33 million tonnes of polymer waste [3]. In Europe, nearly 25 million tonnes of polymer were eventually turned into garbage in 2012; around 38 percent of this discarded polymer was accumulated in landfills, 26 percent was reprocessed, and 36 percent was retrieved by energy harvesting techniques [4]. These statistics suggest that the volume of polymer debris in the landfill has become too high. Plastics' natural deterioration could take billions of years because the molecules that make up carbon, hydrogen, nitrogen, and chlorine are kept together by extremely intense bonds [5]. As a result, the daily deposition of plastics in landfills causes a significant environmental danger. Researchers established recycling strategies to reduce the amount of plastics in landfills [6]. Nevertheless, reprocessing polymers is a time-consuming and expensive procedure that necessitates a lot of manpower to separate out the polymers and pollutes the water [7]. Various polymers have various properties like the resin compound they are made of, colour, and opacity, therefore screening is needed before reprocessing. Since polymers are predominantly extracted from petroleum, another process for transforming polymers directly into usable types of energy and chemicals for industries is the energy extraction technology.

Polystyrene (PS), an inexpensive and durable polymer, is one of the extremely essential and commonly utilized. It is translucent, but colorants could be used to colour it. It is heat resistant, lightweight, and has excellent endurance and longevity, making it ideal for a wide range of requirements. Packaging, toys, and household products such as desktop housing and kitchen equipment are among the implementations. PS is accessible in two forms extended and solid, both of which are able to be recycled. Nevertheless, once reprocessed, extended polystyrene foam residue ends up losing its foam features. It is practical to re-gas the recovered

polystyrene, but this raises the price of the commodity relative to new material. As a result, it is used in solid state molding processes. Formation of polystyrene from styrene by free radical vinyl polymerization, is shown in figure 1.



Fig. 1 Formation of polystyrene

PS wastes, both extended and solid, have been conveniently reprocessed into extruded plastic lumber. Extruded polystyrene (XPS) has been commonly used in the construction of walls, roof trusses, and flooring for buildings and homes. PS foam is commonly utilized as an insulating material, while reprocessed PS is utilized to make plant pots, pens, and pencils, among other items. Expanded PS could also be used as a substrate for the processing of poly-electrolytes with better flocculation properties than industrial Praestol 2515 [8].

PS from both reprocessed and virgin sources is mixed to create a composite that has almost identical features to wood. In terms of physical looks, density, and structural characteristics, this unique component is remarkably similar to wood, making it a viable choice for use in the furniture and infrastructure projects. Non-foam polystyrene substances, such as HIPS, OPS, Styrofoam, post-industrial commodities, and post-consumer products, are accepted as recyclable substances [9].

In underdeveloped nations, a substantial amount of PS trash is thrown away as a solid source of pollution. Furthermore, the growing utilization of PS in electronic devices has intensified the growth of trash from electrical and electronic equipment (WEEE), exacerbating the problem. Furthermore, a substantial quantity of increased PS is regularly discarded at wholesale markets, supermarkets, department stores, restaurants, and shops, as well as machine fabrication plants. It is then obtained as a reusing product by the recycling workers. Nevertheless, prior to actually reprocessing PS, the corporations must weigh a range of factors, including eco-friendliness, corporate social responsibility, hygienic considerations, and record keeping. Even before recycling, waste products should be thoroughly cleaned to eliminate any trapped food or dirt particulates, metallic covers and glass containers should be removed from unprocessed

materials and extra large products should be compressed to fit comfortably into the garbage and transportation vehicle. Different methods, such as dissolving in solvent, heating, and pulverizing, could then be used to decrease the amount of PS residue.

Pyrolysis is the most common approach for treating polystyrene, which requires thermal decay without the use of air to generate pyrolysis oils or gases, as well as monomer or other useful chemicals [10]. The pyrolysis method necessitates the choice of suitable reactors and catalysts to regulate the pyrolysis temperature and end-products. Many researchers have based their work on the effects of reactor design (such as batch-type, fixed-bed, continuous flow, and pressure reactors) and materials [11–15]. The use of solvents, different polymer combinations, and additives for pyrolysis has also been considered to be an effective approach for increasing liquid product yield [16,17]. Many studies have been performed on the pyrolysis of PS using acidic and basic catalysts to increase product yield and selectivity while also achieving a low-cost pyrolysis process [18–22]. This review paper addresses some of the above concerns and provides an up-to-date study of the different approaches for pyrolysis of PS waste that have been used so far. This graph depicts the global distributions of polystyrene (PS) production potential by area in 2016. Asia was the worlds leading country in terms of polystyrene manufacturing capacity in that year, accounting for 55.1 percent of worldwide capacity.

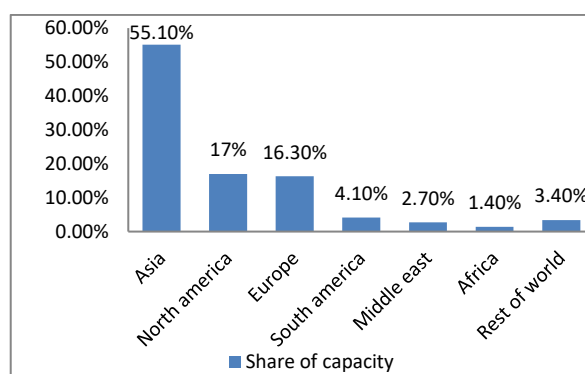


Fig.2 Distribution of polystyrene production capacity worldwide in 2016, by region, source: statista.com 2021

II. TYPES OF POLYSTYRENE ACCEPTED FOR RECYCLING

The common white substance, extended polystyrene (EPS) foam packaging, is specially designed to stabilize, insulate, and secure all forms of goods throughout transportation and could be reprocessed. EPS insulation boards utilized in residential and industrial buildings, foodservice items manufactured of PS resin foamed to deliver a special insulating consistency, and loosefill packaging are all suitable for recycling. Non-Foam Polystyrene goods, also

known as high impact polystyrene (HIPS), directed polystyrene (OPS), post consumer goods, post industrial goods, and styrofoam, are also recyclable [23].

A. Mechanical recycling

Toyomasa [24] patented a Japanese patent that proposes compressing PS foam retrieved as waste and heating it to melt to decrease its volume David et al. [25] have identified a method and apparatus for reclaiming waste polystyrene-type products for recycling within the standard ranges of the input polystyrene-type substance. Disintegration of wasted polystyrene-type substances in a dissolve segment using a reused solvent with a low boiling point and high vaporization rate, elimination of solid substances in one or even more filter parts, devolatilization of the submerged PS, and retrieval of the polystyrene-type content in a solid state in a regeneration section are all part of the reported method and apparatus. The method and equipment should generally have a closed system with the vaporized solvent being recycled and reused. In the restoration section, the highest temperature is 190C. The environmentally sustainable reusable solvent should have a low boiling point and a moderate vaporization rate. The ideal reusable solvent for this method is propyl bromide or environmentally stable blends thereof, which include blends with isopropyl alcohol.

Marcello et al [26] proposed patent which suggests the utilization of dialkyl carbonates as a solvent for expanded PS, filtration to remove insoluble materials, selective precipitation of PS with a non-solvent or a blend of non solvents, isolation, drying, and extrusion of the precipitated PS. This method enables pure PS to be recovered without affecting its characteristics.

B. Chemical recycling

Koji et al [27] demonstrated how to make a PS foam that could be reprocessed into styrene by combining PS with a catalytic decomposition catalyst and foaming the blend with an inert blowing agent. When it's no longer usable, it could be decomposed into styrene by heating it to 300–450°C in a non oxidizing setting. The common oxides are Na₂O, MgO, CaO, or similar compounds, with CaO being the most appropriate. When a simple metal oxide borne by a porous inorganic filler is being utilized, its usefulness can be increased. A nitrogen gas, a chlorofluorocarbon, propane, or something similar is utilized as a blowing agent.

Bajdur et al [8] developed sulfonated expanded PS waste products that could be utilized as polyelectrolytes. Improvement was carried out using well-known techniques, and components with different sulfogroup concentrations in the polymeric chains were acquired. The polyelectrolytes

have strong flocculation properties, comparable to anionic commercial polyelectrolytes, according to the researchers.

Ukei et al.[19] investigated the breakdown of PS into styrene, which include monomer and dimer, utilizing solid acids and bases such as MgO, CaO, BaO, K₂O, SiO₂=Al₂O₃, HZSM5, and active carbonas catalysts. Solid bases were considered to be more efficient catalysts for the breakdown of PS into styrene than solid acids. This was due to the fact that PS's deterioration mechanisms varied from those of solid acids and bases. When thermally broken down PS was introduced to BaO powder at 350C, it was observed as being the most powerful catalyst amongst those solid bases used, and about 90% of PS was transformed into styrene.

At 310–370C and 6.0MPa strain, Ke et al [28] investigated the breakdown of PS in different supercritical solvents such as benzene, toluene, xylene, and others. PS was effectively depolymerized into monomer, dimer, and other components in a short reaction time with a high conversion rate. Although the conversions of PS were similar in all of the above solvents, toluene used as a supercritical solvent was more successful than other solvents such as benzene, ethylbenzene, and p-xylene in recovering styrene from PS. The maximum yield of styrene extracted from PS in supercritical toluene for 20 minutes at 360 degrees Celsius was 77 weight percent.

C. Thermal recycling

Polystyrene (PS) is completely fabricated of styrene monomers derived from petrochemical liquids. A long hydrocarbon chain of phenyl groups connected to alternate carbon atoms makes up this compound. Due to the extreme challenges in sorting and processing polystyrene, the bulk of polystyrene waste is actually discarded off in landfills rather than reprocessed. This poses a danger to the environment and harms humans, wildlife, and marine life. As a result, converting polystyrene into useful commodities through pyrolysis becomes crucial. Pyrolysis is a method of decomposing lengthy polymeric chains into usable low molecular weight liquid and gaseous commodities by heating polymer at an elevated temperatures of 300–900C in the absence of oxygen. The three primary byproducts of pyrolysis are oil, coal, and char. These byproducts are highly valuable to the manufacturing and processing industries. Without any more processing, the generated fuel oil can be used as a fuel in furnaces, turbines, boilers, and diesel engines.

Batch activity was used to test the thermal degradation of real municipal waste plastics (MWP) from Sapporo, Japan, and model mixed plastics at 430°C under atmospheric pressure

[29]. Fossil fuel consumption, greenhouse gas emissions, and photochemical oxidant precursors are among the tools and environmental consequences measured over the life of each of the packaging. The findings [30] show that recycling and reusing plastic-based commodities could have major environmental benefits.

For high-value petrochemical or fuel feedstock, thermal recycling of post-consumer polymer wastes [31] has been widely studied. The technology for thermal cracking that has been explored more extensively and tested on a bigger level is focused on a fluidized bed, in which solid polymers are fed and sand is utilized to aid fluidization [32]. Since the kinetics of pyrolysis of plastics is subjected to considerable uncertainties due to aspects like heterogeneity of the substance, synergy in the cracking of various components, and heat and mass transfer constraints, the layout of fluidized beds utilized at the laboratory or pilot plant scale has been performed on an empirical basis. These aspects make it impossible to obtain accurate kinetics for reactor design at industrial temperatures i.e above 450°C [33]. Acid catalysts allow for lower cracking temperatures as well as the selective production of industrially relevant commodities [34].

Pyrolysis for the simultaneous production of oils and gases could be useful for obtaining hydrocarbons, recycling crude petrochemicals, and even producing power from plastic wastes. Various constituents of polystyrene (PS) have been pyrolyzed using a Gray-King apparatus [35]. The critical temperatures for pyrolysis were determined by thermogravimetric analysis of plastics waste. To obtain greater liquid yields, the heating rate was kept low. The findings showed that waste PS generated more liquid. Styrene was the most common liquid form of PS waste.

PS wastes in solid and/or liquid state are mixed with a binding material and then processed into pellet form, according to a patent developed by White et al. [36]. These pellets were put into a pyrolysis zone of a furnace, where they were partially gasified. Prior to reaching the sintering region, solid particulates were moved to the furnace's oxidation region while liquid components were enabled to condense. Northemann later patented a system for disintegrating PS straight into styrene monomer [37]. The PS waste was pyrolyzed in a fluidized bed reactor at temperatures ranging from 400 to 700 degrees Celsius. A magnesium or aluminum silicate medium was being utilized to improve the heat transfer rate. With an average dwelling time of lesser than a minute, the PS was depolymerized in the reactor. After that, the styrene was extracted from the gaseous cracking byproducts. Bouziane also revealed a batch pyrolysis procedure for reprocessing PS in order to generate valuable light oil and fuel gases [38]. The charge is inserted

into a rotatable reactor, which is then emptied, rotated, and heated until the exothermic reaction starts. The reactor pressure is then raised to ambient pressure or higher, depending on the situation. Condensable hydrocarbon vapours and gaseous hydrocarbons were developed as a result of the continual rotation and heating. Although the vapours condensed into gasoline, the gaseous hydrocarbons were utilized to heat the reactor. Matsubayashi described recovering styrene from PS in a solvent by supplying solution consisting polystyrene to a pyrolysis system and heating the solution to a temperature at which the polystyrene is cracked and thus styrene is recovered [39].

Yang patented catalytic cracking, in which he combined waste PS with a catalyst like ZSM-5 and placed the charge into a reactor for catalytic cracking [40]. The temperature was held between 280 and 480 degrees Celsius, and solid contaminants were separated from the vapour. In a condenser, the vapour was concentrated, and the condensate was purified and extracted to produce gasoline and diesel oil. Carner, on the other hand, used iridium, manganese, gold, silver, or other metals and their oxides as catalysts [41]. PS residue was combined with the catalyst and a reaction fluid like gasoline. The feedstock is then turned into slurry, which is heated in an evacuated atmosphere to break down the individual PS macromolecules into monomers. Srinakruang illustrated the usage of dolomite catalyst at temperatures ranging from 330 to 400 degrees Celsius in his patent [42]. In a semi-batch reactor, the resulting liquid undergoes a catalytic cracking reaction, yielding higher quality fuel, mainly light and heavy naphtha.

DeWhitt patented a process for handling PS waste in a pyrolysis chamber at temperatures ranging from 270 to 375 degrees Celsius [43]. A vacuum was used to expel the vapor of pyrolyzed inorganic substances and gaseous organic substances from the chamber as it was slowly heated in stages. The vapour was then permitted to come into contact with a pH buffered aqueous media, which caused gaseous organic substances to condense. The oil products were isolated from the inorganic elements, which include chlorine and bromine. To generate pyrolysis gases, McNamara et al. pyrolyzed PS in an oxygen-free environment [44]. Long-chain gas elements condensed and re-pyrolyzed to cause thermal degradation as these gases come into interaction with plates of a contactor vessel. Short-chain gas elements, on the other hand, bypass the contactor vessel, resulting in one or more on-spec fuel commodities. Bordnyuk patented a new reactor for pyrolysis of PS at temperatures ranging from 340 to 445 degrees Celsius by cracking the hydrocarbons stored in it [45]. PS is transformed into hydrocarbon compound-containing vapours. The hydrocarbon substituents were divided into various petroleum commodities using separating

vessels based on their boiling points (diesel, gasoline, furnace fuel, kerosene, propane, butane, ethane, and methane, etc.). The fuels developed throughout the processing are able to be recycled and can be used in upstream applications.

D. Traditional Breeding And Genetically Modified Crops

Additional alternative is to utilize genetically modified crops (GMC), which can enhance total power generation of industry in a variety of manner including: (i) increasing solar energy conversion by modifying photosynthetic pathways; (ii) enhancing protection against pest and diseases ; (iii) water shortage resistance to adapt energy crop plants to the impacts of climate change and (iv) cold resistance to adapt energy crops to the impacts of cold climate; (v) cultivation in marginal lands like saline or contaminated land to address environmental issues and achieve a profitable activity; (vi) lowering of management power requirements like tilling, harvesting, and transport; (vii) significant decrease of fertilizer implementation through utilizing engineered plant for Nitrogen fixation or enhancing mineral capitation efficiency; (viii) alterations of lignin composition can also enhance the biomass conversion to biofuels; (ix) multiproduct generation for instance, the cellulase generation by maize which might decrease the price of costly enzymes for the biofuel transformation of cellulose [23]. Some of these can be obtained by conventional breeding at lesser cost, but need longer periods of time.

Sustainable primary resources continue to be a significant concern for large corporations. Pulp and paper mills that could make bioethanol from forestry materials are the finest representation of bio refineries nowadays. These could grow into large-scale chemical plants or local biofuel stations.

III. CONCLUSION

In today's world, the most common form of disposing of polystyrene waste is landfill, which is ineffective due to its slow degradation rate, which poses significant environmental impacts. In this case, pyrolysis of PS seems to be the best method for transforming PS into usable products. Furthermore, the pyrolysis procedure is beneficial because it could reduce the dependence on non-renewable energy sources such as fossil fuels.

PS pyrolysis has proved to be a reliable and efficient process for producing a number of useful hydrocarbons that could be used as chemical feedstocks or as a replacement for non-renewable fossil fuels. Pyrolysis is more environmentally sustainable than other processing approaches because it takes place in an oxygen-free environment, preventing the generation of dioxins and reducing carbon monoxide and dioxide emissions. It's also a versatile technology that could

easily combine temperature, strain, and residential time variations to achieve the desirable end-products. At lower temperatures, the pressure that regulates pyrolysis may be a factor. Nonetheless, as opposed to other variables such as temperature, the impact of pressure on pyrolysis is understudied. This parameter needs further study by researchers in order to find a feasible solution to the problem of attaining high operational temperatures throughout pyrolysis.

Pyrolysis could take place in a thermal or catalytic atmosphere, but the catalytic procedure needs relatively low functioning temperatures and produces more liquid oil. According to the results of the experiments, the operating temperature for PS pyrolysis is 425°C. The highest amount of liquid oil is produced at this temperature. The ideal temperature, on the other hand, is largely determined by the form of by-products we want to extract. If liquid oil is desired, a temperature range of 300–500°C is suggested, whereas if gaseous or char by-products are desired, a temperature greater than 500°C is desired.

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