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Review on Identification, Recycling and Degradation of Polystyrene

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Abstract: ***The main aim of this article is systematically to carry out comprehensive review on polystyrene, its identification, recycling and degradation. Polystyrene is a versatile plastic used to make wide variety of products. It is polymer of styrene and pentane which is blowing agent. Identification of polystyrene can be done through different methods like FTIR, GC-MS and DSC which gives satisfactory results. Various types of plastics have very slow degradation rate. It ranges from 10-1000 years depending on type of plastics. So there is need to recycle polystyrene. Commonly used recycling methods are chemical, mechanical and thermal recycling. These methods have their pros and cons. Recycled polystyrene has limited applications. So to control plastic pollution recycling and degradation of polystyrene both are important. Degradation of polystyrene with thermal, catalytic, supercritical solvent oxidation, photocatalytic and biodegradation are useful to convert it in less harmful component(s).***
Keywords: polystyrene, FTIR, GC-MS, DSC, recycling, degradation, etc.

I. INTRODUCTION

Environmental pollution due to plastic is a global problem nowadays. Plastic pollution can alter habitats and natural processes, reducing ecosystem's ability to adapt to climate change, directly affecting millions of people's livelihoods, food production capabilities and social well-being [1]. Plastics are polymers consisting of a large number of repeating molecule units, monomers. There are different types of plastics like polyethylene, poly (ethylene terephthalate), polypropylene, polystyrene and polyamide are common plastics in municipal solid waste, while acrylonitrile–butadiene–styrene, poly(butylene terephthalate) and polycarbonate are mainly found in industrial mono waste streams [2]. The estimated degradation times for plastic bags tend to fall into one of two ranges: 10−20 years or 500−1000 years, while that for "plastic" bottles is reported as over 70 up to 450 years. In some paper, it is reported that "plastics" do not degrade at all. In these claims, however, the type of plastics is often unclear, and the environmental conditions are not specified. Also, the extrapolation method is unknown. Each of these factors has a large impact on degradation times [3]. Approximately, 58% of plastic waste is land filled or released into the environment directly, 24% is incinerated, and only 18% of the plastic waste is being recycled worldwide. Due to their long persistence time in nature, the amount of global plastic pollution in the natural environment including landfills is estimated to occur around 12,000 MMT by 2050 [4].

II. POLYSTYRENE

Of the world's plastic production, at least 6% corresponds to polystyrene (PS) [1]. Commercial production of PS was started in the1930s by the German company BASF (I G Farben) and was introduced into the USA in 1937 [5]. There is about 21 million tons of PS produced in the world in 2014 [6]. Polystyrene is commonly produced in three forms namely extruded polystyrene, expanded polystyrene foam, and extruded polystyrene foam, each with a variety of applications [7]. PS has been mainly used in four types of product: GPPS, high impact polystyrene (HIPS), PS foam, and expanded polystyrene foam [6]. Polystyrene or Styrofoam (Expanded Polystyrene EPS) is one of the plastic which is used widely as protective packaging materials [8 and 9]. In 1954, the Dow Chemical Company invented expanded PS, which is widely recognized as an excellent insulating medium for buildings and as a mouldable packaging material [5]. Due to its reasonable durability, strength and lightness, polystyrene is used in variety of applications including in food packaging, electronics, construction, medical, appliances, toys and many more [10]. Styrofoam is a trade name of expanded polystyrene (EPS) composed of about 5% polystyrene (PS) and 95% air [8]. Polystyrene copolymers are also produced; these contain one or more other monomers in addition to styrene. There are also europlex-35, pinoplex, PSB- 15, 25, 35 types of expanded polystyrene foam of different grades and density used in Russian construction [11]. General purpose polystyrene (GPPS) is clear, hard, and rather brittle. It is an inexpensive resin per unit weight [7]. Polystyrene can be recycled and it has the number "6" as its recycling symbol [12]. Unrecycled polystyrene, which does not biodegrade, is often abundant in the outdoor environment, particularly along shores and waterways, and is a form of pollution [7].

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A. Chemistry

The chemical makeup of polystyrene is a long chain hydrocarbon with every other carbon connected to a phenyl group. Polystyrene's chemical formula is $(C_8H_8)_n$; IUPAC name is Poly (1-phenylethane-1-2-diyl) [4, 13]. Polystyrene is a thermoplastic substance, which is in solid (glassy) state at room temperature, but flows if heated above its glass transition temperature (for molding or extrusion), becoming solid again when cooling off [7]. PS can be solid or foamed while the monomer styrene is liquid. PS is a rather poor barrier to oxygen and water vapor and has a relatively low melting point [6]. Polystyrene has a moisture content of 0.25 wt. % and fixed carbon content of 91.34 wt. % [14]. Because it is an aromatic hydrocarbon, it burns with an orange-yellow flame, giving off soot, as opposed to non-aromatic hydrocarbon polymers such as polyethylene, which burn with a light-yellow flame (often with a blue tinge) and no soot. Complete oxidation of polystyrene produces only carbon dioxide and water vapors [7]. Polystyrene is chemically unreactive this is why it is used to create products such as containers for chemicals, solvents and foods. This stability is the result of the transformation of carbon-carbon double bonds into less reactive single bonds. The strong bonds within the molecule make styrene very stable [7]. In recent years the expanded polystyrene composites with cellulose and starch have also been produced [7].

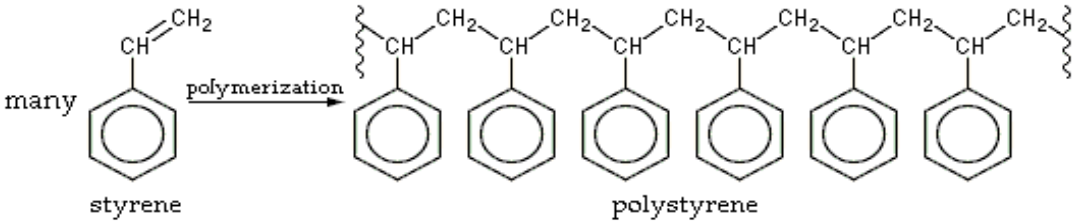

Fig. 1: structure of polystyrene *[7]*

Density of PS	1050 kg/m^3
Density of EPS	25-200 kg/m^3
Dielectric constant	2.4-2.7
Specific gravity	1.05
Electrical conductivity (s)	10-16 S/m
Thermal conductivity (k)	0.08W/(m.K)
Young's modulus ©	3000-3600Mpa
Tensile strength (st)	46-60Mpa
Elongation at break	3-4 %
Notch test	2-5 KJ/m^2
Glass temperature	95ºC
Melting point	240ºC
Vicat B	90ºC
Linear expansion coefficient (a)	8 10-5/k
Specific heat ©	1.3Kj/(kg.K)
Water absorption (ASTM)	0.03-0.1
Decomposition	X years, still decaying

TABLE 1: Physical properties of Polystyrene [7]

III. STYRENE

Benzene and ethane are the starting compounds for anthropogenic styrene production where both are derived from petroleum through ethylbenzene. In 1996, the world production of styrene was reported to be 14,700,000 tonnes. From the total styrene production, 65% of styrene was used to make polystyrene [15].

Styrene, the simplest alkenyl benzene, is an unsaturated aromatic monomer, which is known by several alternative names such as phenyl ethylene, vinyl benzene, styrol, and cinnamene. It is a colourless, oily liquid with a penetrating sweetish odour that is lowly soluble in water and can undergo spontaneous polymerization even at room temperature (Mooney et.al 2006).

Molecular weight	104.15
Density	0.909
Boiling point	145.15ºC
Melting point	-30.6ºC
Heat of polymerization	-69.8 KJ/mol
Vapor pressure (25ºC)	0.67kPa
Solubility in water (20ºC)	300mg/l
Henry partition coefficient (air to water)	0.21

TABLE 2: Physical properties of styrene [7]

A. Polymerization of Styrene

1) Radical Polymerization**:** The initiator used is a radical, and the propagating site of reactivity is a carbon radical [7]. The most commonly used initiators are peroxides and azo compounds [17].

2) Cationic Polymerization: The initiator used is an acid, and the propagating site of reactivity is a carbocation [7].

3) Anionic Polymerization: The initiator is a nucleophile, and the propagating site of reactivity is a carbanion [7]. Until few years ago, anionic polymerization is the only way of producing polymer of near uniform molar mass, block copolymers, star shaped polymers and polymers with variety of terminal groups [17].

4) Coordination Catalytic Polymerization: The initiator is a transition metal complex, and the propagating site of reactivity is a terminal catalytic complex [7].

5) Dispersion polymerization: It was performed to synthesize monodisperse polystyrene nanospheres with narrow size distribution. Ethanol as reaction medium containing polyvinylpyrrolidone (PVP) was poured into batch-type reactor where the temperature was maintained as 70 °C [18].

IV. IDENTIFICATION OF POLYSTYRENE:

A. FTIR (Fourier Transform Infrared Spectroscopy)

The chemical structures of the model polystyrene and the commercial products based on this polymer were confirmed by recording their IR spectra [19]. The FTIR spectra of liquid products of thermal and catalytic degradation of PS indicated the specific vibration bands of the functional groups methyl, methylene, aromatic ring, vinyl double bond and C-CH_3 bond from the branched structure of the compounds from liquid products [20]. FTIR is fast, accurate, and widely used for compound identification [21]. In the FTIR spectra of control polystyrene, the signature peaks of PS include 3354 cm-1, 2979 cm^{-1} ,2917 cm^{-1}, 2148 cm^{-1},1487 cm^{-1} , 1324 cm^{-1}, 1042 cm^{-1}, 877 cm^{-1}, 748 cm^{-1} (C-H bond stretching), 1645 cm^{-1} (C = C bond stretching), 1445 cm^{-1} (CH2 + C=C bond stretching), 1152 cm^{-1} (C- O bond stretching), 1083 cm^{-1} (C-O-C bond stretching) [22]. The FTIR spectra of weathered polystyrene microplastic showed spectral changes correspond to the formation of new bands at 3360–3240 cm^{-1} (hydroxyl group), 1640 cm^{-1} (double bond or C¼O groups), and 1100 cm^{-1} (C-O bonds) [51].

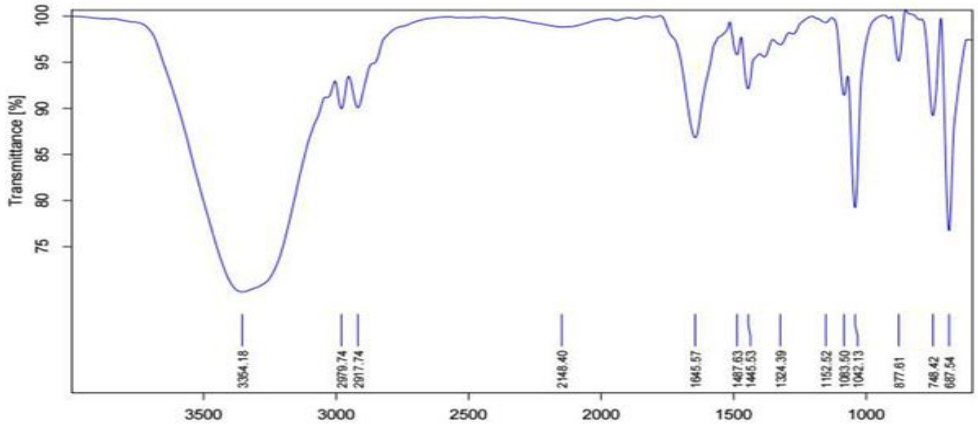

Fig 2: FTIR of polystyrene [51]

B. GC-MS analysis (Gas chromatography and mass spectroscopy)

Polystyrene is thermally decomposed and the generated gas analyzed by GC-MS. Results showed that the liquid products contain mainly styrene monomer (up to 55.62%), toluene, ethylbenzene, 1-methylethylbenzene, α-methyl styrene and 1,1'–(1,3-propanediyl) bis benzene [20]. Polystyrene used for milk packaging identified by GC-MS. Twenty compounds were determined by GC-MS, from which styrene was major component found in milk. The concentration level of styrene in plastic is 524 mg/l and found in milk is 13mg/l [54]. For GC-MS quantitative analysis, a styrene gaseous standard was used to prepare a calibration curve. The calibration curve was prepared by injecting 5, 10, 25, 50, and 100 mL of 1 ppm standard gas into 1 ppm gaseous standard styrene. SIM chromatograms (Selected Ion Monitoring) of the measured styrene under the experimental conditions for 104 m/z at linearity levels. In the mass spectrum, the base peak at 104 m/z was used for quantitation of styrene, whereas 103, 78, and 72 m/z were used as reference ions [52]. The pyrolyzate styrene compound of PS also showed indicator ion under the defined pyr GC-MS condition was 104 m/z. For styrene dimer and trimer, it was 130 m/z and 91m/z [53].

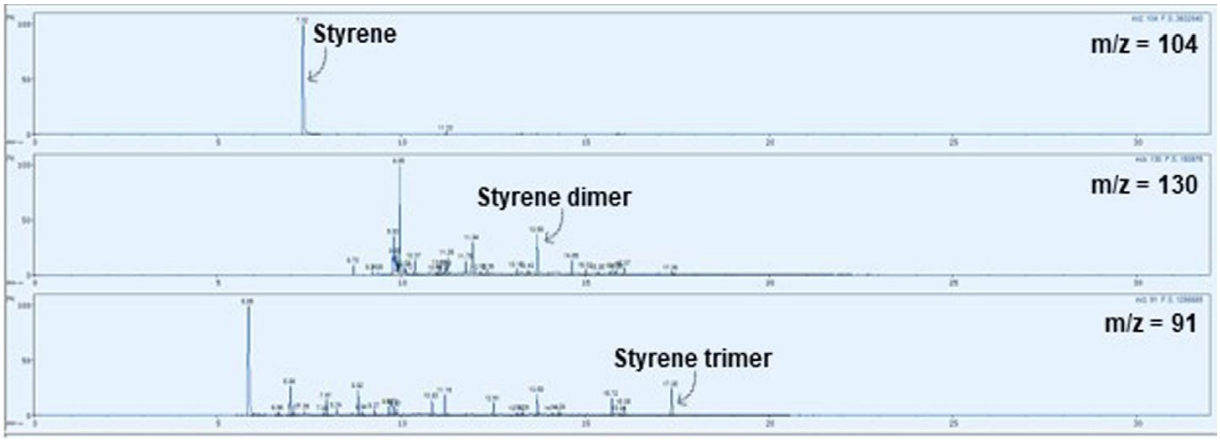

Fig 3: Chromatogram showing extraction of polystyrene ion *[53]*

C. DSC (Differential Scanning Calorimetry)

DSC is a thermal analysis apparatus measuring how physical properties of a sample change, along with temperature against time [23]. Tg (Thermogravimetric) measurements of the model polystyrene and commercial samples, as well as of the polymers produced after polymerization, can be performed using a differential scanning calorimeter. T_g can be calculated using a well-known procedure at the point where a change in the slope of the curve can be observed [19]. The content of volatile substances in the samples (polystyrene and fullerene polystyrene) was determined by thermos-gravimetric heating up to 423 K with a scan rate of 10 K min^{-1}. A mass loss about 2% is observed due to evaporation of volatile substances (styrene oligomers and solvent traces) from the films [25]. The glass transition temperature of pure PS pellets obtained from DSC thermograms comprised Tg= 106^{O}C. Therefore the temperature range for polymer processing taken 200–220^{O}C, while the mold temperature had to be below 100^{O}C [50].

V. RECYCLING OF POLYSTYRENE

A. Thermal recycling

The process for recovering valuable chemical and petrochemical products from plastic waste is the stepwise thermal degradation of polymer mixtures. It allows step-by-step simultaneous separation of the different product fractions generated by the polymers of the blend [26]. Thermal degradation of PS has been investigated in the presence of water. The experiments were carried out in closed systems under inert atmosphere, in the temperature range 300–350^{o}C, at pressures up to 18 MPa, for 1–120 h. The products obtained, separated as gases, volatiles, and heavy compounds, were analyzed qualitatively and quantitatively by gas chromatography, gas chromatography-mass spectrometry, and size exclusion chromatography. The results showed that the presence of water increases the yields of the volatile products, mainly in the first steps of the pyrolytic process, and leads to higher yields of monomer. This latter observation suggests a lowering of the secondary reactions extent [6]. Several transitions can be seen in thermal degradation of foamed polystyrene. The starting and ending temperature changes with polymer density. Maximum volatilization was observed at 430^{o}C [27]. 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.).

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The fuels developed throughout the processing are able to be recycled and can be used in various applications [28]. Pyrolysis was done on PS waste in a fluidized bed reactor at 400-700°C. To improve the heat transfer rate, magnesium or aluminum silicate medium was utilized. PS was depolymerized in the reactor with the average time was lesser than a minute. Valuable light oil and fuel gases were also generated by reprocessing PS in batch pyrolysis procedure [29]. Thermal recycling involves the use of high temperatures to break down EPS waste. It is cost-intensive and also contributes to greenhouse emissions. Temperature regulation and the quality of the recycled product are other issues with thermal recycling [13]. There is no such good way for individuals to recycle EPS easily [30].

B. Mechanical recycling

Mechanical recycling gives solid PS and also liquid PS in a pure form without altering its properties, which can be used again [6]. HIPS (High impact polystyrene) is a promising material for mechanical recycling, since its properties are not extremely affected after multiple processing up to nine cycles [31]. The utilization of di-alkyl 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 was suggested. This method enables pure PS to be recovered without affecting its characteristics [28]. The mechanical method has the major limitation of the mechanical means of recycling EPS is the issue of cost and quality of the final product. It is worth noting that the quality of recycled materials is often lower when compared with virgin material. It is not always cost-effective [30]. Polystyrenes are challenging to collect and recycled due to their low densities. Solid PS can be mechanically recycled into other useful products whereas expanded polystyrene (EPS) usually requires a solvent-based or mechanically based method to de-foam and reduce its volume before reprocessing. Solvents used to de-foam EPS do not cause degradation of the chains but care must be taken to minimize the environmental and carbon impact of the solvent of choice.

C. Chemical recycling

PS foam can be recycled into styrene by mixing a PS with a basic metal oxide being a catalytic decomposition catalyst and foaming the mixture with an inert blowing agent. The basic oxides are NA_2O, MgO, CaO, etc. and among them CaO is desirable [6]. Sulphonated derivatives of expanded polystyrene waste foam was synthesized, which can be used as polyelectrolytes. It is found that polyelectrolyte has good flocculation properties than anionic commercial polyelectrolyte [32]. Degradation of PS into styrene using solid acids and bases like MgO, CaO, BaO, K_2O, SiO_2/Al_2O_3, HZSM5 and active carbons catalysts. It was found that solid bases were more effective catalysts than solid acids for the degradation of PS into styrene. This was attributed to differences in the degradation mechanisms of PS over solid acids and bases. Among the solid bases employed, BaO was found to be the most effective catalyst [33]. Chemical method is complex because most chemical methods require research expertise and experience which also limits the commercialization of the various findings. Some of the chemicals used in chemical recycling are costly and not environmental friendly like toluene, xylene, etc. releasing toxic substances in the environment [30]. PS cannot be easily recycled to its monomer by simple chemical methods. Instead, thermochemical recycling techniques such as pyrolysis is usually applied [6].

VI. DEPOLYMERIZATION OF POLYSTYRENE

A. Pyrolysis

Pyrolysis process can produce liquid oil up to 80 wt. % at a temperature of about 500ºC, so it has received a lot of attention from the scientific community [29]. PS can be thermally depolymerized at relatively low temperature to obtain the monomer styrene with a high selectivity [35]. A thermal decomposition process that involves heating the polystyrene at high temperatures in the absence of oxygen, leading to the breakdown of the polymer into smaller hydrocarbons, including styrene and other liquid hydrocarbons [7]. Pyrolysis and gasification are now recognized as promising routes for the upgrading of solid wastes to more usable and energy dense materials, such as gas fuel and/or fuel oil, or to high value feed stocks for the chemical industry. The characterization of pyrolysis behavior of plastic wastes is then significant in the optimization of pyrolysis processes for the recovery of valuable product fractions. Moreover, a pyrolysis step is always present in the initial stages of gasification and combustion processes [42]. The organic compounds influenced the yields of thermal polystyrene degradation was investigated at 400°C and 60 min. The components generated from PS waste were identified as toluene, ethyl benzene, styrene, and methyl styrene. The primary component is styrene. Although the liquid yields were not dependent on used organic compounds, the styrene yield depends on used organic compounds. Styrene yield was the highest in naphthalene and the lowest in diphenylamine. The amount of styrene was found to increase in the following order: diphenylamine <thermal <phenol <quinone <naphthalene [36]. Pyrolysis process in a pressurized autoclave reactor was also performed [43].

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The experimental duration was one hour and was conducted at a temperature of 300°C-500°C. The heating rate used was 10°C and the pressure applied was in the range of 0.31MPa-1.6MPa. From the experiment, the oil yield obtained was around 97.0 wt. % at a temperature of 425°C. Maximum gas production was only 2.5 wt. % [44]. PS can be thermally depolymerized at relatively low temperatures in order to obtain the monomer styrene with a high selectivity. The pyrolysis of PS in a laboratory fluidized bed reactor in the temperature range 450–700^{o}C was performed and 98.7 wt. % of liquid oil at a temperature of 600°C given high yield. The yield of styrene reached a maximum of 78.7 wt. % at 600^{o}C [44] as well as 65 wt. % yield of styrene using a fluidized bed reactor at 580^{o}C also obtained [45]. Since the oil product contained a high percentage of styrene monomer, the possibility of using it directly for the reproduction of the polymer was further investigated. Results show that this product can be polymerized to produce a polymer similar to the original PS [19]. In the same experimental reactor at 520^{o}C reported the generation of an oil composed of 82.8% w/w of styrene by other researchers. This was achieved by further distillation of the liquid fraction after pyrolysis [34]. The yield of styrene monomer from the pyrolysis of polystyrene has been reported that the best condition for the production of styrene is working at 800^{o}C with polymers having a molecular weight higher than 10000. The production reaches then 80% [46].

B. Mechanochemical Depolymerization

Depolymerization of the addition polymer polystyrene to monomeric styrene is facilitated by mechanochemical processing at room temperature under ambient atmosphere. The reaction occurs in metal-based milling media in concert with scission of macromolecular chains that generates carbon-centered free radicals detectable by EPR spectroscopy [49].

C. Catalytic Depolymerization

Polystyrene waste was depolymerized by using various acidic and basic catalysts. Among the metal oxides, calcium oxide was found to be the cheapest and most effective catalyst for the depolymerization of waste polystyrene into styrene. Metal carbonates provided pure styrene, but in low yields. Acids were found to be poor catalysts for depolymerization, since they led to further reactions leading to side products [47].

VII. DEGRADATION OF POLYSTYRENE

In 2018 United Nations Environment Programme report states that PS “can take up to thousands of years to decompose” [34]. Scientific studies of plastics degradation times are evolving, and estimated lifetimes can change dramatically based on new evidence [3]. A recent study found that polystyrene exposed to sunlight degrades on much shorter time scales than the thousands of years in previous estimates [34].

A. Thermal degradation

PS can be thermally depolymerized at relatively low temperature to obtain the monomer styrene with a high selectivity [35]. A thermal decomposition process that involves heating the polystyrene at high temperatures in the absence of oxygen, leading to the breakdown of the polymer into smaller hydrocarbons, including styrene and other liquid hydrocarbons [7]. The organic compounds like diphenyl amine, naphthalene, phenol influenced the yields of thermal polystyrene degradation was investigated. The primary component is styrene. Although the liquid yields were not dependent on used organic compounds, the styrene yield depends on used organic compounds. Styrene yield was the highest in naphthalene and the lowest in diphenylamine. The amount of styrene was found to increase in the following order: diphenylamine <thermal<phenol<quinone<naphthalene [36]. Benzene, toluene, ethylbenzene and p-xylene were used as supercritical solvents to depolymerize polystyrene with a novel quick degradation process. Toluene used as supercritical solvent gave higher yields of styrene than other solvents [13]. The most efficient catalyst in the thermal degradation of polystyrene waste was found in Florisil. Also natural volcanic tuff is an efficient and cheap catalyst for degradation of polystyrene waste and can produce a higher quantity of styrene monomer (54.16%) [20].

B. Catalytic degradation

Catalytic degradation has been researched widely. By the help of suitable catalysts we can lower the temperature of thermal degradation from 873 to about 650 Kelvin in addition catalysts also make the process fast with low production of undesired products. Thermal and catalytic degradation of polystyrene waste over two different samples of natural zeolitic volcanic tuff catalysts comparative with Florosil catalyst has been carried out in order to establish the conversion degree into styrene monomer [20]. It gives different yield with different catalyst ranging from 59 wt. % to 79 wt. %. In catalytic degradation of polystyrene, solid acids like HZSM-5, HY, mordenite, silica–alumina and clinoptilolite were screened for their performance.

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Clinoptilolite showed good catalytic performance for the degradation of PS showing selectivity 99% towards aromatics. Styrene was the major product followed by second product ethyl benzene. Higher selectivity to styrene is observed at higher temperatures [37]. Styrene can be produced by catalytic degradation with the help of different types of catalyst like MgO, CaO, BaO, K_2O, and $SiO2/Al_2O_3$, etc. [7]. In some experiments, solid bases were found to be more effective for selective degradation of polystyrene to styrene. Among solid bases like CaO, MgO, etc. barium oxide was most effective that 85% of polystyrene was recovered as styrene monomer or dimer. It was also found that the amount of BaO powder dispersed in the polystyrene films necessary to complete their degradation into styrene is as small as 1 wt. % [4] but some research resulted that MgO is the most effective catalyst, with minimum residue. Approximately 83 wt. % of polystyrene was converted into styrene when MgO catalyst was used for the degradation at 400 °C for 2 hr. [4]. Styrene was separated from the liquid by fractional distillation at 145 °C (bp of styrene). The molar refraction calculated for styrene with MgO is 36.379 and for standard styrene monomer is 36.380, compared to CaO and BaO (36.358 and 36.368, respectively). Among the catalysts investigated, the properties of the liquid derived with MgO catalyst are in close agreement with the styrene monomer [38].

C. Photo-catalytic degradation

Waste polystyrene can be converted to styrene by simple photo-catalytic degradation at room temperature. The main problem of photo-catalytic degradation was found to be low (30-35%) efficiency of degradation of polystyrene [7]. Solid-phase photocatalytic degradation of polystyrene (PS) plastic over copper phthalocyanine (CuPc) sensitized TiO2 photocatalyst (TiO2/CuPc) has been investigated under fluorescent light irradiation in the air. PS degradation under ultraviolet irradiation may be initiated directly by photons attacking PS to create excited states, followed by chain scission, branching cross-linking, and oxidation. The PS photodegradation exhibit that higher PS weight loss rate, lower PS average molecular weight, less amount of volatile organic compounds, and more CO2 can be obtained in the system of PS-(TiO2/CuPc), in comparison with the PS TiO2 system. It showed that it is useful way to photodegrade plastic contaminants in the sunlight [55].

D. Super critical solvent oxidation method

Supercritical water oxidation (SCWO) is a rapidly emerging-waste-treatment method that has attracted many researchers' interests. Supercritical water dissolves polystyrene, which does not dissolve in water at ambient temperature and atmospheric pressure. Various investigators obtained high yield of styrene monomer using SCWO to pyrolysis polystyrene. Though SCWO has many advantages in cracking polymeric materials, simultaneously it causes rapid corrosion to apparatus at so rigorous operating condition (temperature over 380 °C and pressure over 20 MPa).

The supercritical degradation of polystyrene using supercritical toluene, ethyl benzene, benzene, and p-xylene has been recommended to increase the yield of liquid. At 360^{o}c, toluene gives highest yield among all the supercritical solvents which is 77%wt. This recovery was the highest among the experimental conditions investigated, thus indicating that there is an optimal condition to obtain the highest yield of styrene [13].

E. Biodegradation of polystyrene

In 1974, using the consumption of oxygen, it is examined that the bio-oxidation of plastic fragments (including photodegraded PS) in natural soils and sewage sludge [39]. Using β-^{14}C labelled PS as substrate, researchers observed $^{14}CO_2$ evolution in soil and liquid enrichment cultures, and isolated common soil microorganisms of the genera *Pseudomonas*, *Bacillus*, *Nocardia*, and *Micrococcus* [40]. Similarly, by monitoring on $^{14}CO_2$ production, 17 species of fungi in axenic cultures were tested for their abilities to degrade PS, and extremely low decomposition rates (0.04 to 0.57%) were found [41]. A two-step pyrolysis and bacterial conversion combinational strategy was reported to convert virgin PS to a biodegradable thermoplastic, namely polyhydroxy alkanoate (PHA). In this approach, PS has been converted into styrene oil by pyrolysis, and then supplied as the only carbon source for the growth of *Pseudomonas putida* CA-3 and for PHA accumulation [34]. From the gut of *Tenebrio molitor* and *Zophobas morio* special microbes with PS plate and PS turbidity system with time courses were analysed. Two strains TM1 and ZM1 which isolated from *Tenebrio molitor* and *Zophobas morio*, and identified by 16S rDNA sequencing. It showed that TM1 and ZM1 used PS plate as carbon source [56]. *Pseudomonas* species Y2 is able to grow on styrene, ethyl benzene, 2- phenyl ethanol, 1-phenyl ethanol, acetophenone, phenyl acetate and mandelate as a sole source of carbon and energy. Salicylate, 2 –hydroxyl phenylacetate, 1- and 2 -phenyl ethanol are produced from styrene [48].

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VIII. CONCLUSION

Due to increasing demand of polystyrene, there is increasing waste of polystyrene. In today's world, the common polystyrene disposable place is in landfills. Due to its slow degradation rate, its impact causes severe danger to the environment. Recycling and degradation methods of polystyrene are not environment friendly and can harm the environment. Complete degradation of polystyrene may take five hundred years. So practically it is not possible to complete degrade polystyrene. The common degrading processes for polystyrene are thermal, catalytic, photocatalytic and super oxidative solvent oxidation but these are also not efficient processes to degrade complete polystyrene. To reduce the increasing pollution due to polystyrene, biodegradation is the only source. This review will help for further studies and encourage the scientist to research on biodegradation of polystyrene.

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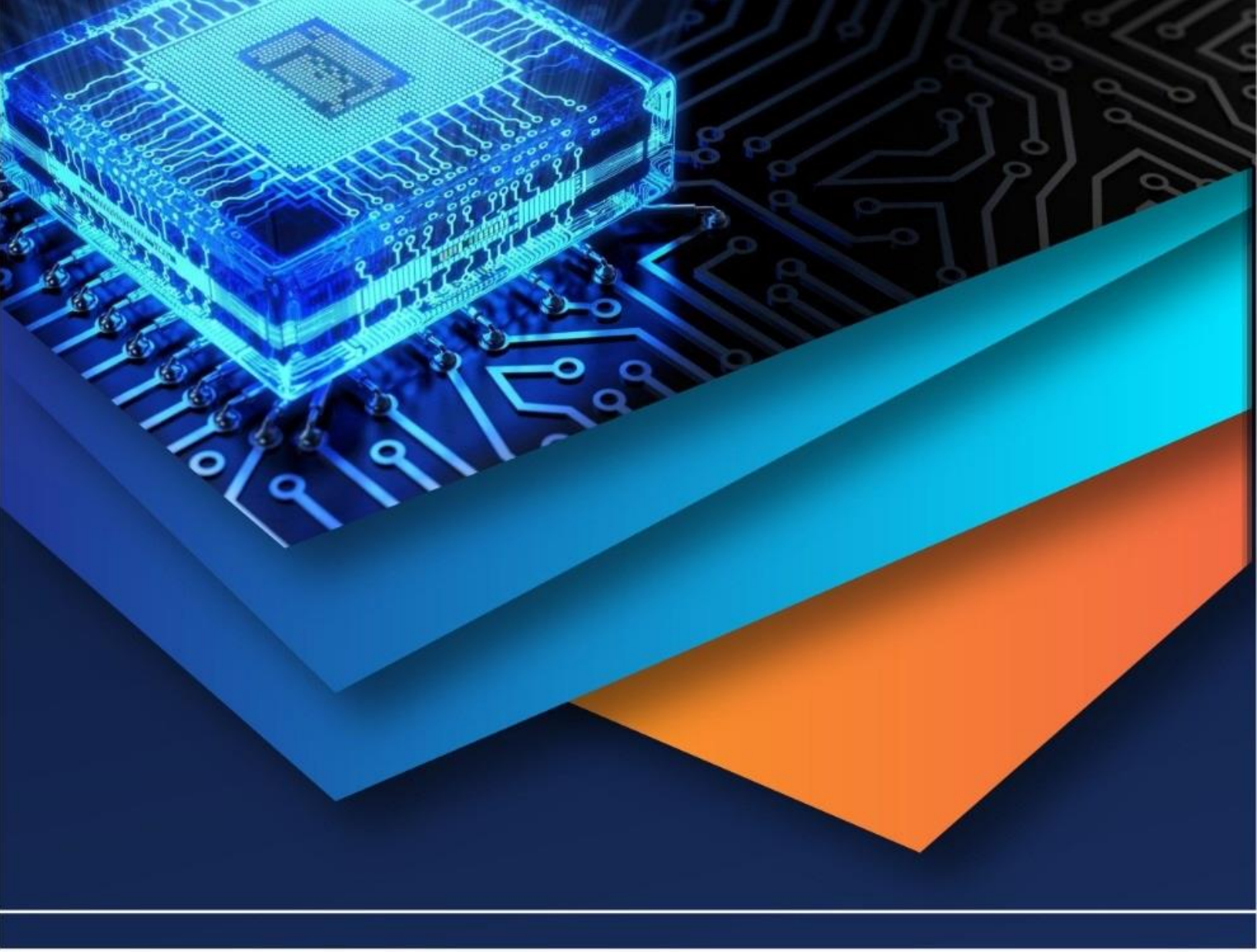

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