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(REVIEW ARTICLE)

A mini-review on expanded polystyrene waste recycling and its applications

SHADRACK CHUKWUEBUKA UGWU * and CHIZOBA MAY OBELE

Department of Polymer and Textile Engineering, Faculty of Engineering, Nnamdi Azikiwe University, Awka, Nigeria.

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Abstract

Over the years, waste recycling has been a growing concern among many nations of the world, especially in developing countries. Expanded polystyrene (EPS) is used in electrical/electronic appliances as a shock absorber and constitutes a reasonable percentage of the entire plastic waste. There are three methods of recycling expanded polystyrene: mechanical, chemical, and thermal recycling; each of the above methods gives rise to different products that are used in different applications. Expanded polystyrene is used as a binder in emulsion paint as a replacement for conventional binders; as a component of asphalt used in road construction; as a component of wood plastic composites; as a blend with silica and in concrete to produce lightweight construction material. This article studied the various applications of recycled polystyrene waste from mechanical, chemical, and thermal methods of waste recycling.

Keywords: Expanded polystyrene (EPS); EPS Applications; Recycling; Plastic Waste; Methods of Recycling

1. Introduction

Over the years, there has been a rapid rise in the consumption of plastics around the globe [1-3] The use of plastics in many industries such as packaging, automobile, and several constructions are on the rise [4] Plastics are quickly turning into a global challenge right from its discovery even though it has a great many applications. Researchers have shown that some of the chemicals used in the production of plastics are harmful to the environment and marine life [5]. Furthermore, the indiscriminate disposal of plastic waste has led to blockages of waterways leading to flooding and other environmental hazards. According to data from the United Nations environmental program, between 1950 and 2017, about 9.2 billion tons of plastics were manufactured globally [6]. However, approximately 7 billion of these tons of plastics that were produced ended up either buried, burnt in incineration, or deposited in a landfill. Going further, in Sub-Saharan Africa, as the human population is rapidly increasing, so is the volume of plastic (waste) generated thereby making waste management difficult especially plastic waste. Researchers have shown that only about 15-25 per cent of the produced plastic waste in Africa is recycled while the rest is dumped in open areas or landfills [7].

Generally speaking, plastics used for packaging applications occupy a higher percentage of the entire volume of plastics produced globally. For instance, according to Premalatha, Prathiba [8], global plastic manufacturing is to the tune of 380 million tons annually; only the packaging industries consume approximately 40% of this volume of plastics produced. Handling and disposal of these plastics after use have been of great concern to researchers, governments, and other stakeholders [9]

On the other hand, expanded polystyrene (EPS) is a synthetic synthetic polymer derived from petroleum. It is frequently used in insulation materials, disposable coffee cups, coolers, and other packaging applications. Furthermore, expanded polystyrene and other polystyrene derivatives constitute great environmental pollution when disposed of in landfill because they are not biodegradable [10]. EPS waste can linger in the environment for many years; therefore, a lot of regulations and programs have been put in place by different governments to minimize the amount of EPS (and other

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* Corresponding author: UGWU SHADRACH CHUKWUEBUKA

plastic waste) generated, promote recycling, and ensure proper waste management. At wholesale marketplaces, households, and retail stores like electrical appliance stores, a substantial volume of expanded polystyrene is released after use as well as at industries when new machinery is bought. However, these EPS wastes are usually disposed of in a landfill or burnt in incinerations; the former results in material loss, and it is not cost-efficient while the latter emits toxic and carcinogenic substances into the atmosphere thereby harming the environment and human health [11] Consequently, both public and private sectors are keen to discover more efficient means to mitigate the menace of these plastic wastes that will lead to recovery of materials and energy [12].

This mini-review is therefore centred on exploring various attempts and approaches researchers have employed to reduce, reuse and recycle expanded polystyrene waste as well as various post-consumer applications of expanded polystyrene waste. It is expected that this review will give insight into past and present trends as well as prospects of expanded polystyrene waste. To achieve this, this mini-review will look at the three fundamental waste approaches to waste recycling which are mechanical recycling, chemical recycling, and thermal recycling intending to discuss advances in these methods of waste recycling. Additionally, this mini-review will discuss various applications of EPS and other scholarly approaches to putting EPS into a useful application.

2. Expanded polystyrene waste recycling

2.1. Waste recycling

Recycling refers to the process of turning post-consumer waste into useful products [13]. Waste recycling is the most efficient method of waste management; the importance of waste recycling cannot be over-emphasized. According to Hossain, Poon [14] as compared with other methods of waste management, recycling material waste leads to natural resources conservation. This is true because recycling helps to cut down on the demand for virgin resources such as wood, oil, minerals and petroleum products. Furthermore, for others like Shih, Lin [15] recycling promotes environmental protection because it helps in the reduction of pollution emanating from wastes as well as pollution that comes from the extraction and processing of raw materials. Additionally, it aids in lowering greenhouse gas emissions which is a catalyst for climatic change. Going further, waste recycling helps in reducing the number of wastes that reach landfills and waste dumps thereby minimizing the possibility of land and water contamination and also helping in land conservation [16]. Most importantly, waste recycling is opening a new field of opportunities and employment creation as the topic of waste recycling is of growing emphasis in many fields like construction, manufacturing, and transportation [17]. More so, recycling helps in saving money because it helps to lower the price of raw material extraction and processing.

Despite the advantages of recycling EPS waste, there are still difficulties that must be overcome, including the necessity for specialized collection and recycling facilities, the high cost of recycling technology, and the lack of consumer awareness and incentives for recycling EPS waste effectively.

2.1.1. Expanded Polystyrene Waste Recycling

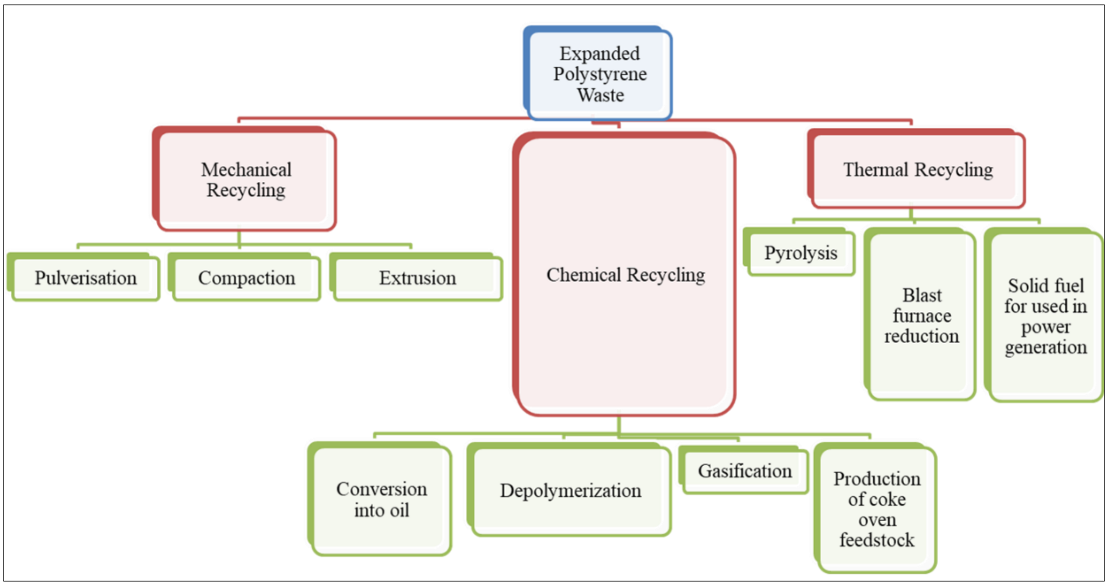
Although expanded polystyrene is an adaptable and lightweight material that is frequently used for packaging, insulation, and padding, it can take so many years for it to break down when disposed of in the environment. Therefore, recycling and safe management are very crucial.

There are three methods of recycling expanded polystyrene which are:

- Mechanical recycling
- Chemical recycling
- Thermal recycling

The overview of the various routes through which expanded polystyrene can be recycled is shown in figure I below.

Mechanical recycling of EPS involves the use of machines (mostly extruders and compacting machines) to reduce the volume of EPS waste, melt it, and then mould it into useful products [18]. On the other hand, chemical recycling entails reducing EPS waste to its monomer or solution using suitable solvents. While thermal recycling entails the degradation of EPS waste by subjecting it to regulated high-temperature heating to cause a breakdown of long-chain hydrocarbon. A detailed explanation of the methods of EPS waste recycling is given below.



[Adopted from: http://www.eps-recycling.net/wpcontent/uploads/2010/11/three-recycling-processes.jpg]

Figure 1 Possibilities of recycling PS

2.2. Mechanical recycling

Generally, the three different types of polystyrene are Solid Polystyrene, expanded polystyrene foam and polybutadiene reinforced form (HIPS); and all of them find application in packaging. Solid polystyrene can easily be mechanically recycled into useful products but expanded polystyrene most times needs solvent-based or mechanically based processes that can de-foam and reduce its volume before processing [19]. The mechanical recycling of expanded polystyrene waste involves the initial, sorting, washing and drying followed by size reduction (in form of flakes or granules) in a milling machine before further treatment such as solvent treatment; extrusion (In case of blend in wood plastic composites) or direct blending can be carried out [20]. The milled EPS powder can also be used as fine aggregate filler in much other plastic processing. The pulverization method of EPS recycling involves grinding EPS into smaller pieces (pulverizing) so that it can be remoulded into new expanded polystyrene products or used as a filler in other products. The advantages of this method are that it reduces waste, conserves resources, and decreases the environmental impact of EPS production and disposal. Modern plastic sorting methods involve the hybrid of automated and manual operations; basically, Near Infrared (NIR) are utilized to identify the polymer type and the optical colour method also aids in the sorting of plastics into clear and coloured fractions [18]. Other complementary sorting technologies are X-rays, Density, Electrostatics, melting points, selective dissolution and manual sorting.

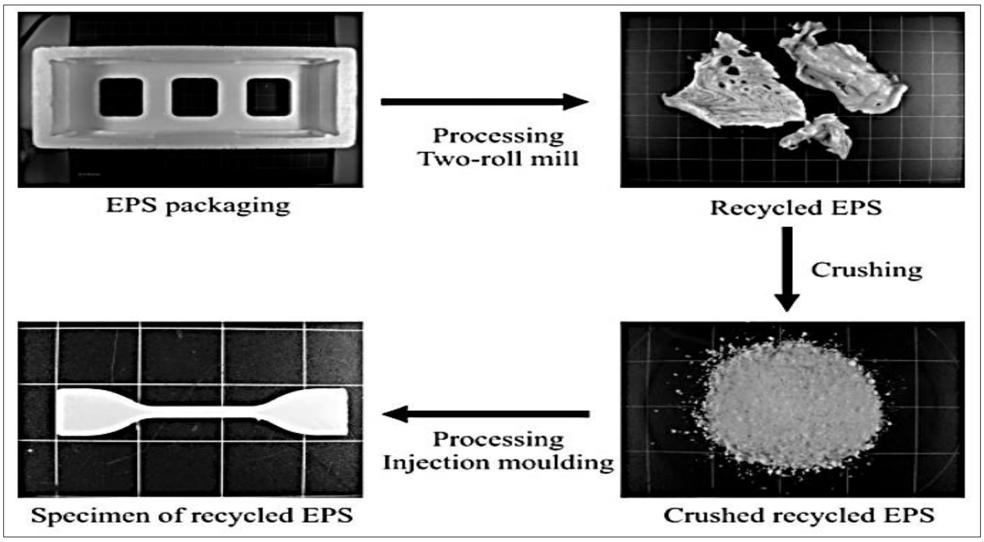


Figure 2 A typical mechanical recycling of EPS waste (source:[20])

Figure 2 above shows a typical mechanical recycling of expanded polystyrene waste.

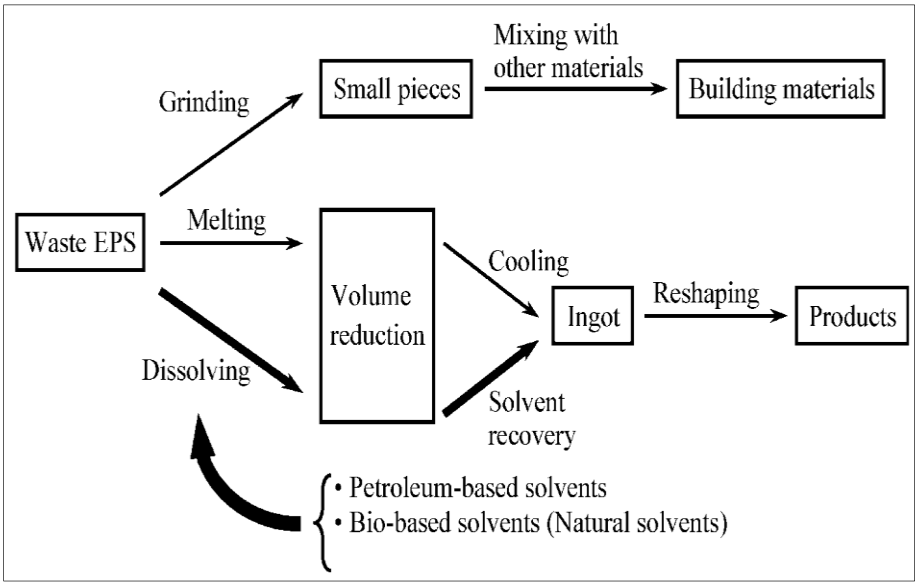


Figure 3 Expanded polystyrene recycling systems (source: [21])

According to the study by [20], the volume-expanded polystyrene waste can be reduced mechanically in a milling machine (crushing) without an appreciable loss in properties. Furthermore, [22] after reducing the waste expanded polystyrene waste (WEPS) to 2-4 mm spherical shapes and used the aggregate to make lightweight concrete for application in lightweight construction. Their study revealed that the compressive strength of the product ranges from 11 MPa to 900 MPa which aligns with the internationally accepted standard of 17MPa. Additionally, [23] reported the conversion of crushed expanded polystyrene to nanofibrous mats used in filtration applications. They achieved this through the electrospinning process by dissolving EPS in Dimethylformamide (DMF) and d-limonene solvents after size reduction.

Researchers have identified granulation as a mechanical method for recycling expanded polystyrene; this process involves shredding EPS into small pieces and then melting it to form small beads. For instance, [24] used granulated EPS to synthesize a core of a silicate sphere coated with a special liquid glass-based mixture and treated it with CO_2 in the process of forming polystyrene-silicate mineralized granules. More so, compression is another mechanical means of recycling EPS which involves compacting EPS waste into blocks or logs which can then be used to create new EPS products. This method was reported by [25] who used a two-stage process to recycle polyolefin-based plastic wastes for application in soundproof or noise-reduction facilities. They were able to actualize this by mixing polyolefin-based waste and other waste like expanded polystyrene, coir pith, and plastic-coated aluminium foils and then reducing the volume of these mixed waste by 30 times in a two-stage compression moulding process. Their result revealed an enhanced sound absorption property and improved mechanical properties. Similarly, [26] developed a thermal insulation composite (NTIC) in which EPS beads and industrial solid waste are combined for non-structural applications of the compression method of energy saving in buildings.

Other mechanical methods of expanded polystyrene waste recycling are extrusion via the compaction method, which involves melting EPS waste in an extruder and then shaping it into new products such as plastic sheets or pellets and injection moulding in which the melted EPS is injected into a mould to form a new product [27, 28]. The two compactors mostly used are the hydraulic cylinder type and the screw compactors [29]. However, the screw type is preferable because it gives a relatively more efficient process as it is difficult to regulate the pressure under the hydraulic type.

2.2.1. Advantages/limitations of mechanical recycling

Generally, when compared with the chemical and thermal methods of EPS waste recycling, the mechanical method of waste recycling has advantages such as eco-friendliness as there is no release of volatile organic compounds (VOC) or offensive odours associated with petroleum-based EPS solvents [30]. Furthermore, mechanical recycling does not degrade the EPS as in the case of thermal recycling; therefore, it is energy-efficient. Additionally, the mechanical method of EPS waste recycling is cost-effective because it involves a more direct process. This method of recycling can be used to produce a wide range of products such as plastic lumber, EPS insulation products and so on.

Conversely, the major limitation of the mechanical means of recycling EPS is the issue of cost and quality of the final product [30]. It is worth noting that the quality of recycled materials is often lower when compared with virgin material; also, mechanical recycling of EPS is not always cost-effective.

2.3. Chemical recycling

Chemical recycling is a process of depolymerization of the expanded polystyrene to recover the styrene monomer; the most notable of such processes are catalytic degradation [1]. Expanded polystyrene can be reduced to rigid polystyrene by different chemical reactions and the resultant product can be used for different purposes. The reduction of EPS into nano-particles using ethyl acetate has been reported by [31]; their method is represented in figure 4 below.

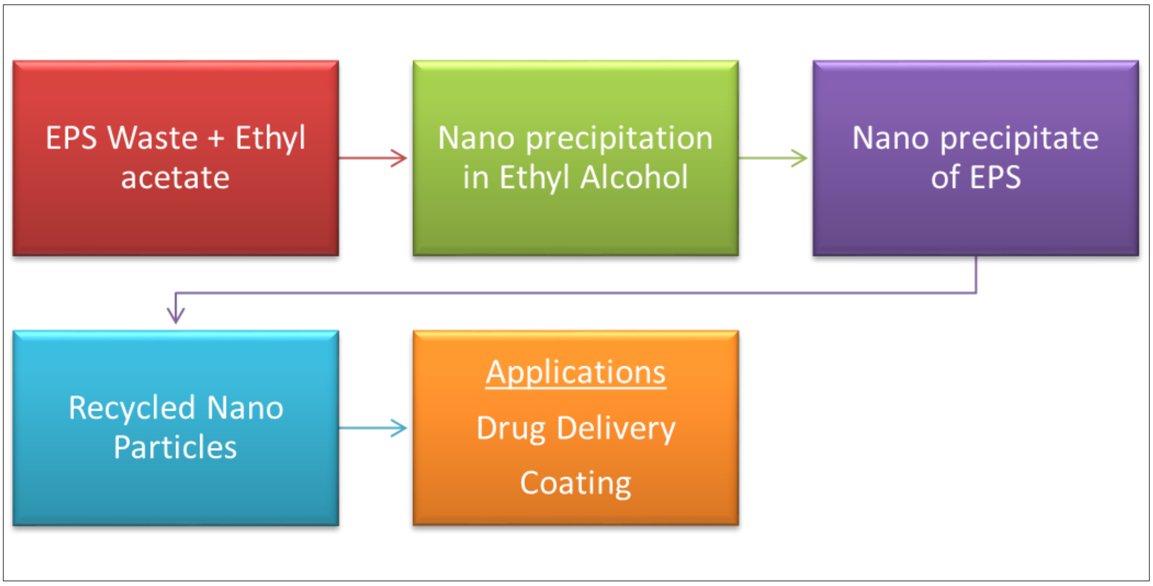


Figure 4 Chemical recycling by nanoprecipitation (Adopted from [31])

From figure 2 above, according to [31], waste-expanded polystyrene was first reduced to nanoparticles by dissolving in ethyl acetate to bring EPS into solution form. They further precipitated the dissolved EPS in ethyl alcohol to form the nano precipitate of EPS which could be further used in drug delivery and coating applications. Also, [32] took a different route by dissolving EPS in styrene monomer in a closed-loop framework. They reported that after the dissolution of EPS in its styrene monomer solvent, they carried out suspension polymerization of the solution to incorporate the monomer (styrene) into the entire mass for further processing. This method is advantageous compared to other chemical methods because it prevents the requirement for solvent as well as polymer separation.

According to a review by Dimitris and Achilias [33], earlier researchers such as Koji et al. (1998) reported the reduction of polystyrene foam, which, when combined with a basic metal oxide acting as a catalyst for catalytic decomposition and foamed with an inert blowing agent, can be reclaimed into styrene. They used basic oxides such as sodium oxide (Na_2O), magnesium oxide (MgO), and Calcium Oxide (CaO) and among them, CaO was desirable according to their report. They also reported decomposing EPS to styrene at the temperature range of 300-450^{0}C in a non-oxidizing atmosphere. Furthermore, Ali et al, (2013) reported the chemical recycling of expanded polystyrene waste to a new functional polystyrene-hydrazone (PSH) surface for the treatment of phenol-contaminated industrial wastewater. Their result shows that recycling of expanded polystyrene was achieved by acetylation of polystyrene followed by condensation with phenylhydrazine. They then employed the manufactured PSH surface for the treatment of phenol industrial water waste; their result demonstrated potential solutions to waste management issues produced by EPS as well as phenol-contaminated water treatment [34]

Furthermore, the Chemical method of recycling EPS involves the use of various chemicals to reduce EPS for other applications. There are various solvent treatments done on expanded polystyrene waste; each of which is aimed at dissolving EPS for subsequent applications. For example, Maharana, Negi [35] used dimethyl glutarate, dimethyl adipate, and dimethyl succinate dibasic esters to reduce EPS. These dibasic esters, when combined with a surfactant, generated a gel-like substance that can be used to waterproof materials or recycled back into PS foam. Similarly, [36] used solvents such as gasoline, toluene, xylene and chloroform and tetrachloroethane (CCl_4) to dissolve expanded polystyrene after constant stirring for 48 minutes except for gasoline. Their result shows that it took a day to form a homogeneous mixture with gasoline. To get a homogeneous solution, they sieve the solution of dissolved expanded polystyrene as solvents only bring the EPS into liquid form. More so, the use of a bio-based solvent, d-limonene a natural vegetable oil from citrus to de-foam and shrink expanded polystyrene has been reported by [37]. Due to the residual oil's role as an antioxidant that prevents chains from scission caused by radicals, this approach reduces the volume of EPS foam by a factor of 20 and is recyclable. According to Noguchi, Tomita [37], D-limonene is a food-derived solvent that may be more environmentally benign than other solvents like toluene, despite the pricey procedure (although the carbon footprint may be significantly larger). Other natural oils including star anise oil, eucalyptus oil, thyme oil, and chamomile oil can be utilized as an alternative to d-limonene to efficiently shrink EPS foam volume without reducing molecular weights [38]. Similarly, David, Steven [39] described a novel process and apparatus for the reclamation of waste polystyrene-type materials. The process involves the dissolution of the polystyrene-type waste in a dissolve section by the use of a reusable solvent (with a high vaporization rate) followed by filtration to remove solid contaminants and devolatilization (recovery) of the dissolved polystyrene-type material in solid form. The maximum temperature of recovery was 190^0C and the solvent used in the process is propyl bromide or isopropyl alcohol.

Going further, the use of dialkyl carbonates solvent has been reported by Marcello and Franco [40]; their method used filtration to remove the insoluble ingredients, and then they further used a non-solvent or a combination of non-solvents to selectively precipitate polystyrene, which was then separated, dried, and extruded. Through this method, they were able to recover pure polystyrene without altering its properties.

2.3.1. Advantages/limitations of chemical recycling

Chemical recycling has its advantages and limitations. The chemical method especially the depolymerization process results in high recycling efficiency as the EPS waste is broken down into its constituent monomer (styrene) [1]. Also, the low energy requirement is another important aspect of chemical recycling when compared with thermal and mechanical methods. Furthermore, chemical recycling is a gateway for discovering varieties of post-consumer applications for EPS wastes. However, a major disadvantage of chemical recycling is the complexity of the process [41]. This is because most chemical methods require research expertise and experience which also limits the commercialization of the various findings. More so, some of the chemicals used in chemical recycling are costly and not environmentally friendly, releasing toxic substances into the environment. Even natural-based solvents such as d-limonene are equally expensive.

2.4. Thermal recycling

Heat is administered to waste as part of the thermal treatment process to decompose it or lower its volume before being reused[42]. Thermal treatment's main goal is to turn waste into a stable and usable product and lessen the amount that needs to be disposed of in landfills [43]. Thermal recycling employs the process of regulated heating or cracking using fluid catalytic cracking at high temperatures and atmospheric pressure to reduce waste. The current methods of thermal recycling are fluid catalytic cracking and pyrolysis [30].

Conesa, Marcilla [44] studied extensively the technology for thermal cracking which has undergone larger-scale testing, and it is based on a fluidized bed in which polymers are fed in their solid state with the aid of sand. Catalysts used in this cracking are acid catalysts which are based on silica-aluminas or zeolites. In a similar study, Arandes, Ereña [45] carried out thermal cracking of polystyrene and polystyrene–butadiene on mesoporous silica.

On the other hand, Pyrolysis is a technology with a prospect that is applied to plastics that are difficult to depolymerize such as polyethene, polypropylene, and polystyrene as well as composites and polyurethanes [46]. According to Qureshi, Oasmaa [47], the advantage pyrolysis has over other recycling methods is that it can handle contaminated plastics which reduces the need for sorting. Pyrolysis is simply the heating of materials (plastics) at moderately high temperatures (450-500^0C, 1-2 atm) in absence of oxygen[48]. This process causes the breakdown of the macrostructure of the polymer to form smaller molecules turning the solid plastics into gaseous, liquid, and solid char fractions [49]. According to [50], pyrolysis in different forms has been used to convert many plastic wastes into useful products. This is because, the pyrolysis process converts large molecular waste plastics into smaller useful hydrocarbons that can be used in varied applications [51] On the contrary, one of the major limitations of the pyrolysis process is the high energy requirement and longer reaction time [52].

Going further, many researchers have made several attempts to use the pyrolysis processes in recycling the expanded polystyrene waste. de Marco, Poletto [53] attempted to depolymerize expanded polystyrene through microwave-assisted pyrolysis using a carbon black catalyst. Their studies revealed pyrolysis of expanded polystyrene at 400W in a fixed time of 12 minutes. Therefore, depolymerization of EPS through a microwave using carbonaceous structures can be a route for EPS recycling. Similarly, [11] reported microwave pyrolysis of polystyrene waste using an activated carbon catalyst. Their studies revealed that there was an optimum oil yield of 93% at a microwave of 450W and polymer to activated carbon ratio of 10:1 which was conducted at a temperature of 330^0C for 5.5 minutes. A typical microwave-assisted pyrolysis set-up for expanded polystyrene is shown in figure 3 below

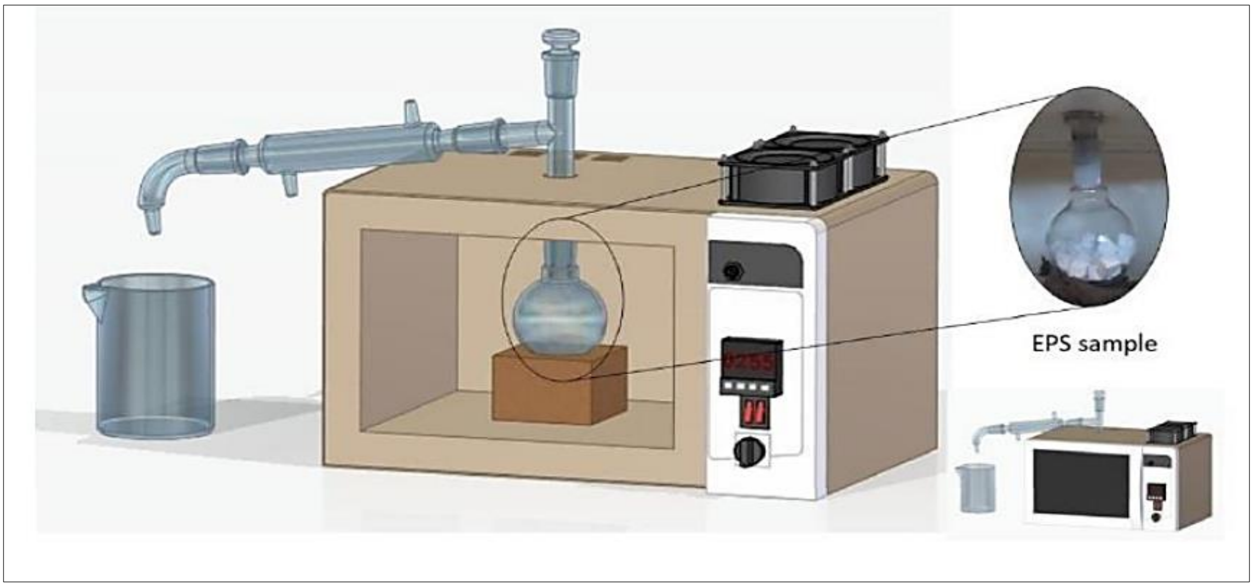


Figure 5 Microwave-assisted pyrolysis of EPS waste set-up (source:[53])

Additionally, Zancanaro, Poletto [54] reported the depolymerization of expanded polystyrene waste using graphene oxide and activated carbon catalysts via microwave-assisted pyrolysis. They varied the quantity of the catalysts being used from 0.125, 0.25, and 0.5g. Their result opines that graphene catalyst depolymerization shows better thermal stability when compared to activated carbon catalysts due to effective heat transfer during pyrolysis. More so, in an attempt to study the effect of temperature on yield during the depolymerization of polymers waste through microwave pyrolysis. Suriapparao, Nagababu [12] varied the microwave temperature in three distinct ranges of 300W, 450W, and 600W using graphite quantities of 50g, 200g, and 350g. Their result suggested that there is an optimum conversion efficiency of 68.1% at a microwave power of 600W and 50g quantity of graphite. Therefore, to a certain degree, there is a positive correlation between temperature and the amount of yield in the pyrolysis process.

From the foregoing discussion, it can be inferred that thermal depolymerization of expanded polystyrene waste using microwave-assisted pyrolysis is one effective way of recycling EPS waste. That notwithstanding, researchers pointed out that depolymerization time, type of catalyst, and temperature play a crucial role in determining the quality and quantity of polymer yield in the process [53]. Also, another important parameter which plays a vital in promoting expanded polystyrene waste depolymerization is using material components that have high thermal conductivity like metals or carbonaceous compounds [54]. According to Bartoli, Rosi [55], these components can enhance heat transfer by absorbing electromagnetic waves and transmitting them to the polymer during the pyrolysis process.

However, the commercializing direct pyrolysis of plastics is not easy due heterogeneity of the plastics as well as the associated limitations to heat and mass transfer; the use of catalysts to lower the operating temperature to avoid complete degradation of plastics becomes necessary. On the other hand, Kan and Demirboğa [42] developed a recycling method based on heat treatment which reduced the volume of expanded polystyrene to about 20 times its original size and correspondingly increased its density. Other properties such as thermal conductivity and compressive strength were also affected by this treatment and they named the product from this method modified expanded polystyrene (MEPS). They were able to achieve this by the heating sample in an oven at different ranges of temperature (110^0c, 120^0c, 130^0c, 140^0c, and 150^0c) to reduce the volume and increase in density which was used in concrete applications.

2.4.1. Advantages/limitations of thermal recycling

Like other recycling methods, thermal recycling has its strengths and limitations. For instance, thermal recycling is a very efficient method of EPS waste recycling as it quickly converts EPS was into usable products *[56]*. Also, because it does not require the use of chemicals, it is equally cost-effective. More so, thermal recycling is versatile and can be applied to other forms of polystyrene products. Some thermal recycling process leads to energy recovery which can be used to power other processes [57].On the other hand, due to enormous energy (high temperature) requirements, thermal recycling is cost-intensive and also contributes to greenhouse emissions. Temperature regulation and the quality of the recycled product are other issues with thermal recycling.

3. Applications of recycled expanded polystyrene waste

One of the important properties of EPS waste that makes it attractive in various applications is its lightweight. The density of EPS ranges from 2-40 Kg/m^3 depending on the type and manufacturing process [58]. Because of this property, it is widely used in lightweight construction. Furthermore, EPS has excellent insulating properties which help to reduce heating and cooling costs thereby making it useful in building construction. Ease of processability is another feature of EPS that attract researchers to explore EPS recycling; it can easily be dissolved in most common solvents which can be used for various applications [59]. Additionally, EPS waste can easily be sorted, cleaned, and readily available. Below are some of the applications of EPS wastes.

3.1. Expanded polystyrene lightweight building block/concrete

Recycled expanded polystyrene waste has been used over the years in the development of concrete for various construction purposes [60]. This is because of some inherent unique properties such as lightweight, durability, good compressive strength, acoustic properties, and insulating properties [61]. Concrete/blocks formed from EPS are made by partial substitution of components with expanded polystyrene in form of beads which are then used for various construction applications. [62] their recent studies incorporated recycled expanded polystyrene waste and kenaf fibre (which is an agricultural waste product) into the concrete matrix for application in interlocking blocks. Their result showed that the interlocking blocks formed from this composite concrete have good properties which were far above the average requirement of 5.2MN/m^2. Similarly, an earlier attempt was reported by Le Roy, Parant [63] who found an indirect relationship between the compressive strength of concrete with EPS and the size of the EPS aggregate. This means according to their studies; smaller sizes of EPS gave concretes/blocks of better compressive strength. For instant, Le Roy, Parant [63] went further to show that comparing concrete with 7 mm beads and a density of 1000 kg/m3 to the same material with 1 mm polystyrene beads revealed a 35% drop in compressive strength.

According to this study, it was possible to adjust concrete with EPS with compressive strength of 20 MPa, by reducing the amount of EPS, or decreasing the water/cement ratio used in developed mixtures. Going further, Medher, Al-Hadithi [64] developed a self-compacting concrete (SCC) using expanded polystyrene beads and different ratios of waste plastic fibre. Their result shows the compressive and flexural strengths of the concrete increased as the percentage of waste plastic fibre increased up to the optimum level.

Production of lightweight EPS concrete follows the same procedure as conventional concrete. Table 1 below shows the effect of expanded polystyrene waste on the properties of concrete produced.

Table 1 Effect of replacement of gravel with Expanded Polystyrene in light concrete

% Replacement of Gravel with EPS	Compressive Strength (MPa)	Density (g/cm^3)
0	23.16	2.32
15	15.07	1.74
20	14.04	1.70
25	12.88	1.65
30	11.38	1.59

Adopted from Carvalho et al, 2019

EPS reduces the compressive strength of concrete but not in a way that can hamper application in lightweight structural applications; the density also correspondingly decreases with the replacement of gravel with expanded polystyrene waste or beads [62].

Figure 6 Recycled Expanded Polystyrene Light Weight Block (Source: [65])

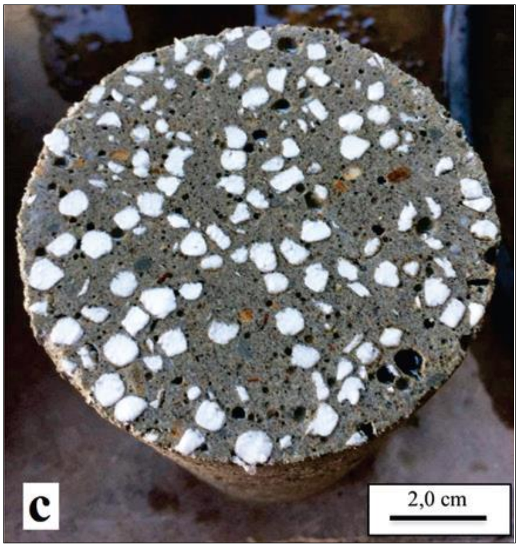


Figure 7 Expanded polystyrene block. (Source:[65])

Not much research has been conducted in the area of the application of chemically modified expanded polystyrene in concrete mixtures. An earlier study by Ravindrarajah, Tuck [66] revealed that the chemical resistance of concretes blended with chemically modified expanded polystyrene was greatly improved as the concretes were unaffected by a solution of saturated calcium hydroxide, 10% sodium sulphate and 10% ammonium sulphate. The concrete also showed considerable durability upon exposure to sulfate or freeze-thaw cycles. Researchers have suggested that the bonding strength of concrete can be improved by incorporating additives such as epoxy resin or aqueous dispersion of polyvinyl propionate but the major limitation is the high cost of such concrete [67].

In a similar report, Assaad, Mikhael [68] showed that virgin or waste-expanded polystyrene can be used as lightweight concrete/mortar for both structural and non-structural use by simply varying its percentage by volume. A major limitation of expanded polystyrene concrete is that they are extremely light with a density in the range of 10-50 kg/m^3 and this brings about segregation in mixing. Segregation encountered during mixing was solved by Eitzen, Ruhl [3] using a technology based upon special pre-treatment of expanded polystyrene particles. This gives the particles the ability to enter into concrete.

3.2. Expanded polystyrene as a binder in emulsion paint.

A viable application of expanded polystyrene is its use as a binder in emulsion paint production. Expanded polystyrene can replace the conventional binders in emulsion paint such as PVA without altering the properties and performance of such a paint. Myint, Zakaria [69] employed recycled expanded polystyrene waste in paint formulation to replace the conventional alkyd resin that is used in some commercial paints. Their result revealed that 27% of waste polystyrene can be incorporated in paint formulation without altering its basic properties. They further showed that the properties of paint produced using expanded polystyrene binder have excellent abrasion resistance, hardness, and resistance to alkali and water when compared with alkyd resin-based paints. Similarly, Osemeahon, Barminas [36] in their study on the most effective solvent for EPS for use as a binder in emulsion paint dissolved EPS in the five most effective solvents namely; gasoline, toluene, xylene, tetrachloroethane (CCl_4) and chloroform. They found out that tetrachloroethane and chloroform cannot be used in the formulation of binder from EPS due to their high vapour pressure which can cause great material properties alterations. This is in support of the study by Fuesers and Zumbühl [70] who also reported a similar result. However, binders formed from EPS using gasoline as a solvent gave properties comparable to commercial binders [36]. Furthermore, Akinterinwa, Osemeahon [71] copolymerized dimethylol urea (DMU) and waste expanded polystyrene (PS) for use as a binder in paint formulation. Their result shows that paint made from DMU/PS exhibited good chemical resistance, and adhesion, and showed acceptable performance when compared with emulsion paint made from PVA. Additionally, Sharma, Gaur [72] investigated the possible application of a combination of cashew nutshell liquid (CNSL) and expanded polystyrene waste (PS) as a binder in emulsion paint. Their result shows that there is an observable improvement in properties for paints produced using CNSL/PS compared to using PS alone.

The discussions above show that expanded polystyrene can be used as a binder in emulsion paint either as a sole binder or a co-binder. EPS is readily available and therefore, can reduce the cost of paint as well as take care of environmental pollution caused by EPS waste. Additionally, the physical and chemical properties of EPS may affect the performance and durability of the emulsion paint. Therefore, further research is necessary to determine the optimal amount of EPS to be used and the potential impacts of its use in paints.

3.3. Expanded polystyrene in asphalt

Researchers have shown that expanded polystyrene waste can be blended with asphalt used in civil engineering road construction. The advantages of such a blend include improved waterproof properties, improved rheological properties as well an increase in rut resistance.

There are several attempts made by researchers to incorporate EPS in asphalt used for road construction and other purposes. For instance, Akter and Raja [73] studied the effect of incorporating shredded waste EPS on the properties of asphalt and asphalt concrete. Their result revealed that properties such as penetration, softening point, ash point, and ductility were all improved with the addition of EPS. More so, they also opined that as the EPS percentage increased, the stability value increased by approximately 82.61% compared to the conventional formulation. Similarly, Gutierrez-Velasquez, Monteiro [74] dissolved EPS in acetone and ethyl acetate to be used as an asphalt adhesive. Their result showed that EPS can be incorporated in asphalt as a coating film or as a binder and it gave a higher mechanical resistance and faster drying time though the viscosity was also higher. Going further, Fang, Jiao [75] reported that asphalt modified with expanded polystyrene has high viscosity at low temperatures and low viscosity at a high temperatures which are required for construction. Also, [76] in their study blended expanded polystyrene waste with asphalt by simply heating asphalt (150^0C) with expanded polystyrene waste to 190^0C. Polymer-modified asphalt (PMA) has greatly improved properties when compared to virgin asphalt such as strong viscoelastic behaviour [77].

Furthermore, penetration values diminish as the number of polystyrene increases, maybe because the adhesive forces between the polystyrene and bitumen component are stronger [73]. Inferring that the material can be utilized in hot temperatures and weather conditions. Furthermore, low penetration grades (60/70) are ideal in warm climates to prevent asphalt softening. High penetration grades are recommended in cold climates [76]. There is also a decrease in the viscosity of asphalt as the quantity of EPS increases.

3.4. Expanded polystyrene in wood plastic composites

Expanded Polystyrene dissolved in acetone can be used as a binder in producing wood-plastic composites. Kaho, Kouadio [78] in their study produced wood plastic composite by dissolving the expanded polystyrene in acetone and homogenizing it in an extruder to produce wood plastic composites; solvent evaporation was achieved in an oven. They opine that recycled wastes can have applications in many fields such as cabinet making for furniture making and building as prefabricated structures. More so, Pao and Yeng [79] combined coconut shell powder (an agricultural waste) with EPS to produce wood-plastic composites (WPC). Their result shows that the mechanical properties of the WPC increased with an increase in coconut shell powder while elongation at break and flexural strength decreased with an increase in coconut shell content. They further revealed that the alkaline treatment of coconut shells helped to improve the mechanical properties of the WPC. Furthermore, Sriprom, Sirivallop [80] used coconut husk fibre and banana stem fibre reinforcements to produce wood-plastic composites based on recycled expanded polystyrene waste. Their results affirm that treating fibre with sodium hydroxide increased the adhesion of fibres to the matrix. Also, they demonstrated that composite with desirable mechanical properties can be formed using EPS waste and natural fibres

Figure 8 Expanded Polystyrene Waste

3.5. Expanded polystyrene in natural rubber (NR) compounding

Although there is hardly any information in the literature about NR–EPS blends, there are some detailed references for studies on thermoplastic elastomers based on NR–PS blends [81].For example, Sekharan, Abraham [82] produced a blend of expanded polystyrene with Natural rubber (NR) by melt mixing NR and expanded polystyrene at 140^{0}C before compounding. They demonstrated that the optimum substitution of NR was at 5% incorporation of expanded polystyrene. Furthermore, they used maleic anhydride as a compatibilizer because NR and expanded polystyrene are non-compatible; the properties of the natural rubber can be compared to that obtained when silica is used. Additionally, Nikulina, Vostrikova [83] produced a wood-polymer composite using expanded polystyrene that reacted chemically with other polymers. Their result shows that the wood-plastic composite has increased hydrophobic properties and higher strength parameters. They attributed this attribute to the cross-linking of oligomer molecules in wood structures with the formation of a wood-polymer framework.

4. Conclusion

This study has discussed the three major methods of expanded polystyrene waste recycling which are mechanical, chemical, and thermal recycling. The mechanical method of EPS recycling involves various compaction, extrusion, and milling processing of EPS which is aimed at producing useful products. The mechanical method has advantages such as eco-friendliness, energy-efficient processes, and varied applications while high cost is one of its major limitations. Also, the chemical method involves the reduction of EPS waste with various solvents or reducing it to its monomer (styrene). Different solvents for EPS include petroleum-based solvents such as toluene, xylene, etc., and some organic-based solvents like d-limonene. Chemical recycling has advantages such as high recycling efficiency, innovative process, and low energy requirement. Additionally, thermal recycling involves the use of high temperatures to break down EPS waste. Thermal cracking and pyrolysis are some of the thermal methods of EPS recycling. Both thermal cracking and pyrolysis involve heating of EPS to high temperature, however, pyrolysis is carried out in the absence of oxygen. Thermal cracking has advantages such as quick processing and energy recovery; however, greenhouse emissions and quality issues are its major limitations.

Furthermore, this study discussed some applications of EPS waste such as in lightweight building blocks/concrete, as a binder in emulsion paint, as a component of asphalt, in wood plastic composites (WPC), and as a component in rubber compounding.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors affirm that there is no conflict of interest in this mini-review article. The article is aimed at providing an insight into expanded polystyrene waste recycling and its application.

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