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Review

A critical review on the influence of energy, environmental and economic factors on various processes used to handle and recycle plastic wastes: Development of a comprehensive index

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ABSTRACT

The conventional methods of waste disposal, namely landfill and recycling, are associated with environmental and economic inefficiencies. The associated policies and regulations are also found to be inadequate in relation to the current situation. The situation of plastic handling-related policies in India was reviewed in this regard. Alternative techniques such as liquefaction, biological treatment, pyrolysis and incorporation of plastics in road laying have received increased attention in recent years. This paper reviews the fundamentals of each process and offers a clear picture of plastic generation and disposal. The present review also focuses on the benefits and drawbacks of different disposal methods by comparing the methods over several economic, environmental and energy parameters. A comprehensive Energy, Economy and Environmental index (EEE index) has been developed in this study to compare the different methods and reconcile the various parameters based on which the comparison was performed. Incorporation of plastic waste in concrete structures and road pavements were found to be the best methods of plastic waste disposal, with an EEE index score of 42.85%. These two methods were followed by pyrolysis and liquefaction of waste plastic with scores of 23.08% each. Landfill, with an EEE index of −7.14%, was found to be the least holistic method of waste disposal and needs to be minimized wherever possible.

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1. Introduction

Plastic are created from a large range of synthetic or semi-synthetic organic substances that are soft and are moulded into solid objects of diverse shapes. The applications that plastic can be used are infinite and inexhaustible (Thompson et al., 2009a,b). The main issue with the plastic is their non-biodegradability. Notwithstanding the fact that plastics are produced from finite non-renewable resources, there are concerns about the effects plastics could cause due to their chemically active precursors. The current pattern of usage are unsustainable as they are known to cause pollution and other ill effects, creating global waste management problems (Thompson et al., 2009a,b). The improper disposal of waste plastic leads to the contamination of the environment it is dumped into. The presence of plastic waste in sewage sludge landfills, municipal wastewater effluent, and plastic mulch from agricultural activities significantly contribute towards the degradation of soil (Chae and An, 2018). Invertebrates have enhanced tendencies to absorb heavy metals into their bodies due to plastic consumption (Hodson et al., 2017). Studies have shown the capability of micro- and macroplastics entering terrestrial food webs (Huerta Lwanga et al., 2017) and have also shown the impacts on terrestrial geochemistry, the biophysical environment, and ecotoxicology caused by plastic pollution (de Souza Machado et al., 2018). Thus, the proper management of plastic waste is a serious issue that must be tackled in a global scale through policy and proper waste management.

The inadequacy of existing plastic handling methods and regulations is particularly pronounced in developing countries with high plastic generation. To highlight the existing policy and process-related limitations, India was selected as an example of a country that fits these criteria. In India, Plastic Waste Management Rules (2016) were put into effect to strengthen the already existing regulations for handling of plastics. The new rule was to ensure that plastic below 50 μm cannot be produced and to phase out the system to multiple layer packing Ministry of Environment and Forest of India, 2016. Plastic Waste Management Rules [WWW Document]. India Environ. Portal. URL http://www.indiaenvironmentportal.org.in/content/426634/plastic-waste-managementrules- 2016/. However, through further amendments in 2018, manufacturers are allowed to claim that their product does not violate the stipulated policy (Venkatesh and Kukreti, 2018). There is still a lack of clarity on the enforcement of the rules laid out in 2018 by the central government (Ray, 2019). A nationwide policy to tackle plastic waste is currently being worked upon by the government, but the success in implementation is questionable (Sharma, 2019). Apart from these policies, the southern state of Tamil Nadu implemented a ban on single use plastics, effective from January 1st 2019 (Tamil Nadu Pollution Control Board, 2020). The state of Maharashtra has also come up with a similar proposal (Sampathkuma, 2019).

Currently about 60% of recyclable plastic is recycled in India, with most of it being down cycled. Like many other countries, the development of a comprehensive waste management policy in India, is still in the nascent stages (Santhosh and Shrivastav, 2019). There is a lack of cohesion in the development and implementation of policies for the handling of single use plastics (SUP), although enforcement of a nationwide ban has been considered. A clear definition of what constitutes as a SUP also seems to be unclear. Currently the alternatives to plastics in India are neither affordable, nor feasible for large scale production or wide consumer usage.

Although a number of technical approaches of materials or infrastructure have been developed to handle plastic waste (such as the production of biodegradable plastic or appropriate recycling procedures), there are two major challenges that remain. First, it is unlikely that rational technical approaches will reduce the dependency on plastic and solve the issues related to its use in a comprehensive manner that is agreeable to all stakeholders. However, that should not prevent spending time and research into finding good alternatives to plastic. Second, there are well-known psychological effects that often undermine technical solutions, such as increased usage after an intervention, which can be loosely termed as 'rebound effects' by the consumer, or an increase in the littering of biodegradable products, which may cause a new set of problems.

Strategies such as recycling may seem to save resources at first glance, but may lead to a change in the behaviour of consumers in the long term, causing them to consume more and thus reduce the overall savings in resources (Marie et al., 2019). The imperative is to explore alternative strategies that involve conversion of plastic into alternate end-products, in order to avoid the negative side effects associated with traditional recycling. Wood-plastic composites is a unique method of recycling using which plastic can be converted to a form that has superior material performance (Winandy et al., 2004), processing and user acceptance (Martinez Lopez et al., 2020). Other methods of handling plastic waste include the treatment of waste by pyrolysis, liquefaction and use of plastic in road and cement construction.

Pyrolysis (devolatilization) is the thermal degradation of an organic substance in the absence of air (oxygen-deficient environment) to produce char, pyrolysis oil, and synthesis gas. Pyrolysis of plastic waste involves the conversion of the same into a mixture of gases, oil, and char, all of which have the potential to be utilized as useful products. The technology is used in the production of various liquid biofuels, which can be used as sources of energy generation. Pyrolysis can be effected in many types of reactors that have been covered in this paper. It is considered to be a tertiary method of recycling, and is an attractive method of dealing with waste plastic. Pyrolysis can be carried out through thermal or catalytic routes. The addition of reactants or catalysts is useful for analytical purposes. However, it is hard to model the overall kinetics since many parallel reactions occur during pyrolysis, causing the usage of lumped analysis for the purposes of modelling (Till et al., 2018).

The technique of liquefaction has been used to on a variety of materials like biomass and sand (Zhang and Zhang, 2020). Liquefaction has been used in the conversion of plastic waste into oil and gas. It can be effected in a high temperature and pressure setup or at moderate conditions (Williams and Slaney, 2007). The process may be conducted alongside biomass, causing the process to then be known as co-liquefaction (Hongthong et al., 2020). However, certain types of plastic waste can be liquefied without the addition of biomass.

Another avenue that has been explored is the use of plastic waste in the making of roads, pavements, and concrete (Duggal et al., 2020). This sustainable type of construction serves a dual purpose. It utilises the plastic waste produced, by converting a resource of low value to a high-value commodity and also serves as a means to improve the quality of roads. Many studies have shown that the usage of sand can be drastically reduced with the incorporation of plastic-based technology (Bale, 2011). These studies have shown that concrete made from recycled plastic by partial removal of the sand component has the same compressive properties as that of structural concrete. The use of plastic in road construction has been employed in many countries such as Australia, Indonesia, India, the United Kingdom, the United States of America, and many other developing countries (Nkwachukwu et al., 2013). These crucial techniques of waste disposal can help reduce costs and environmental concerns all over the world.

Many studies have been carried out in literature analyzing the different plastic waste disposal processes mentioned above. Studies reported in literature have focused on the economic aspect of waste disposal (Hahladakis and Aljabri, 2019), the environmental aspect (Wichai-utcha and Chavalparit, 2019) and the energy aspect (Rigamonti et al., 2014). However, to the best knowledge of the authors, no study has so far combined all three aspects in order to produce a comprehensive assessment of different plastic waste management techniques.

The novelty of this study lies in the development of an Energy, Economic and Environmental (EEE) index which offers a multi-faceted analysis of different techniques used to manage plastic waste, taking into consideration parameters from the fields of energy, economics and the environment. Different factors have been taken into account in order to fully understand the positives and negatives of different techniques and to understand the context in which they can be applied.

2. Methodology for the procurement of relevant literature

The purpose of this review is to highlight and evaluate the various methods by which plastic waste can be handled. The effects of plastic pollution on the environment and human health were extensively covered. The traditional methods of handling plastic were also discussed. Four methods (pyrolysis, liquefaction, tar mixing and concrete mixing) have shown significant scope in the management of plastic waste, and have been discussed in detail. The methods have been compared and contrasted on certain important parameters and the advantages of each method have been highlighted, and the nature of their viability for large-scale use has been assessed.

Various scientific research and review papers, newspaper articles and magazine data from reputed institutions were used in the collection of information and data, through the Google search engine. Scientific findings in these areas were also gathered using Google Scholar, Elsevier and Springer Link were utilized. “Plastic waste pyrolysis”, “Plastic waste liquefaction”, “Plastic waste in road construction”, “Plastic waste in concrete “, “Impact of plastic”, “Types of plastic”, “Uses of plastics”, “Energy consumption in recycling”, “Net energy calculation of plastic waste handling”, “Recycling data” and “Economic impact of pollution” were some of the search terms used.

3. Types of plastic

Plastic can be broadly classified as thermoplastic and thermosets. Most thermosets are non-recyclable in nature and their waste generation improperly managed. Most of the plastic used in India in bulk are thermoplastics. In general, plastic materials are in abundant use in India and are utilized in various sectors as discussed in Table 1.

One of the most common uses of plastic in daily use is for packaging of items, with polyethylene terephthalate (PET) being the main type used. PET can be moulded into various forms to store carbonated or non-carbonated beverages and also used to make plastic films and sheets. Polythene bags are the next most common used form of plastic in India. They are used in many shops in several states as carry bags. Another common plastic used in India is polyvinyl chloride (PVC), which is used in transportation of water in houses. The scene of plastic usage in India has been depicted in Fig. 1. The uses of the various commonly encountered plastics have been discussed in Table 2 (see Fig. 2).

4. Plastic waste management techniques

4.1. Landfills

Landfill is the most primitive method of handling plastic waste. Landfills generate a lot of waste and have been associated with many setbacks. They are not a sustainable method of handling plastic waste, and are hence not discussed in this review in detail. Landfills have known to cause soil pollution.

Another issue commonly associated with on engineered landfills is the leaching of waste into the groundwater reserves of neighbouring communities. Some parameters like the iron, total dissolved salts and chloride content of water can be applied to areas which are at a significant distance from the landfill. Though ‘scientific landfills’ have started to be implemented in India, they are not a model for a sustainable process according to the assessment carried out in this paper.

4.2. Recycling

Primary recycling is the process of re-extrusion of plastic solid waste (PSW). PSW is mainly treated by the process of mechanical recycling, which is one of the most economical ways of recycling waste. The initial step is cutting or shredding in which plastic waste materials are cut by using shears or saws for further processing into small flakes, which are easier to handle. Paper bits, dust and smaller fragments are separated from feed plastic using a cyclone separator in the contaminant-separation process. Plastic waste of different

Table 1
Plastic production in various industrial sectors (Beckman, 2018; Ritchie and Roser, 2018).

Industrial sector	Amount of plastic consumed (in MT)	Percentage of plastic consumed	Plastic waste generated (in MT)	Types of plastic used
Packaging	146	35.9	141	Polyethylene
Building and construction	65	16	13	Polycarbonate, nylon, polyethylene
Other sectors	59	11.5	42	Polycarbonate, nylon, polyethylene
Textiles	47	14.5	38	Polyester
Consumer and institutional products	42	10.3	37	Polyethylene
Transportation	27	6.6	17	Acetal
Electrical/Electronic	18	4.4	13	PVC, melamine formaldehyde.
Industrial machinery	3	0.7	1	Polycarbonate

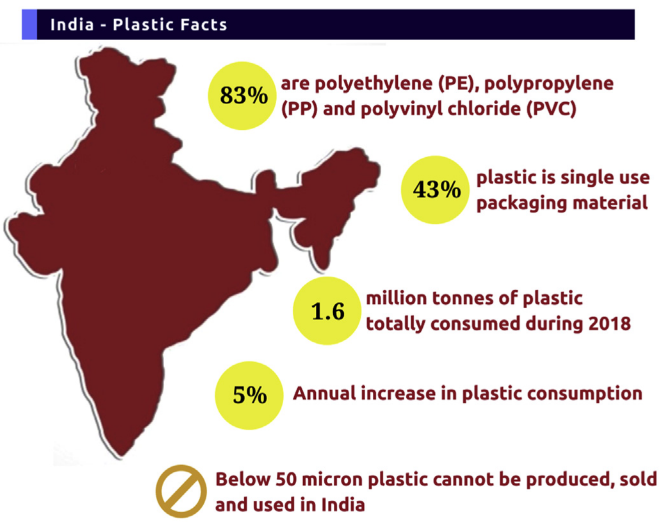

Fig. 1. Statistics related to plastic usage in India (Venkatesh and Kukreti, 2018).

densities are separated by a floatation process in order to deal with plastic in various density stages.

In the next process, milling, the single polymers are collected and milled together. The efficiency of the plant is reduced without the pre-processing stages mentioned before milling. However, when profit maximization is the major goal, these initial stages are not implemented. Afterward, the milled plastic is washed using water. Chemical washing can also be employed in certain special handling of materials (mainly for glue removal from plastic), where caustic soda and surfactants are used.

The products are then gathered in the process of agglutination and collected and stored or sent for further processing. The plastic is extruded to strands and then pelletized to produce a single-polymer plastic. The products are cooled using water at room temperature in the process termed as quenching. The plastic is granulated and then sold in the market in the forms of grocery bags, blinds, shutters, and other household products.

The main principle used in recycling is the remoulding of the plastic material. It is practically impossible to completely convert the entirety of the mass of plastic into another reusable form. This loss of mass in the process of recycling is accounted for as an emission of plastic. Another disadvantage encountered during recycling is the high energy spent in the process. The durability of these products is severely reduced when compared to that of the original product. However, the best course of action by far with respect to plastic is to reduce its use and dependence. Regulations have been instituted to limit the use of recycled materials. Recycled PET bottles for example, cannot be used to pack beverages (Aryan et al., 2019).

One recycling technique that has received progressively increased attention is the production of wood-plastic composites. This method of waste plastic management involves the production of novel materials by combining different proportions of waste plastic and woody waste biomass. The main benefits posed by this technique include the ability to control the properties of the materials produced and the possibility of efficiently removing two different types of waste in the same process.

Panels produced from a combination of automotive plastic waste and macadamia shells have been found to be stronger and more fire-resistant as compared to panels produced singularly from automotive plastic waste (Cholake et al., 2017). Similarly, the mechanical properties of waste plastics were found to significantly increase when used alongside straw flour (Ge et al., 2017). As explained in the same study, the field of producing composites of waste plastic and woody biomass is still in its infancy and requires greater degree of research before being assessed for its long-term viability.

4.3. Pyrolysis

Pyrolysis of plastic waste has been explored as a technique to convert household and industrial plastic waste into fuel through the application of extreme process conditions, in particular high temperature. It involves the degradation of high molecular weight polymeric plastic molecules into lighter liquid and gaseous hydrocarbons, and is carried out in the absence of oxygen to prevent the formation of oxygen-containing by-products such as oxides of carbon and sulphur, in a reactor designed to withstand the extreme conditions (Miandad et al., 2016).

There are two major mechanisms through which it is carried out, differentiated based on whether a catalyst is used. In thermal pyrolysis, high temperature and pressure is applied to the plastic waste, causing the degradation of the molecule through a combination of scission, in which the carbon chain is fractured near the middle, cross linking of chains and cyclization of linear structures (Panda et al., 2010). Thermogravimetric analysis of the kinetics reveals that the vast majority of thermal pyrolysis reactions follow first order kinetics (Grammelis et al., 2009).

Catalytic pyrolysis, on the other hand, involves the usage of a catalyst to increase the effectiveness of the degradation and reduce the energy requirements. It occurs through two possible mechanisms. In the initial stages of the ionic mechanism, the catalyst functions as a Lewis acid or a Brønsted base, facilitating the abstraction of hydride ions from the molecule or the addition of protons respectively. In contrast, the initial phase of the free radical mechanism involves the formation of primary and secondary alkyl

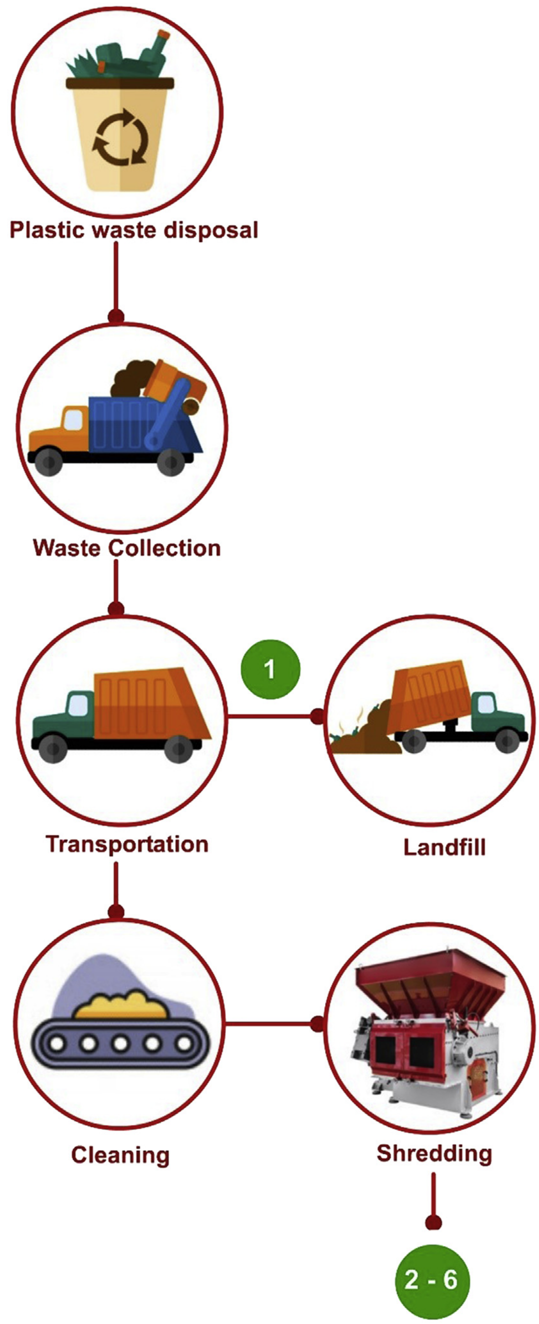

Fig. 2. Overview of Landfill process and shredding of plastic waste. (1) Dumping of waste in Landfill. (2–6) Various other plastic handling techniques.

free radicals from the polymeric molecule in the presence of heat energy and light (Patni et al., 2013). The latter stages of both mechanisms involve a combination of initiation, propagation and termination, with the ionic mechanism also involving isomerization and cyclization of the molecules, different combinations of which yield different sets of products, that are capable of withstanding extreme conditions (Shah et al., 2010), while deactivation of the catalyst can be prevented through steam reforming (Syamsiro et al., 2014).

The most widely used types of catalysts used for pyrolysis are zeolite-based catalysts such as HZSM-5 (Anuar Sharuddin et al., 2016) and Y-Zeolite (Syamsiro et al., 2014), which are made out of a combination of alumina and silica in a crystalline sieve structure, with the former behaving in a more acidic manner when the composition of SiO_2 is low and having the property of near complete regeneration due to the pore diameter being unaffected (Miskolczi et al., 2009).

Fluid catalytic cracking (FCC) has also been used, with silica-alumina crystals held in a zeolite matrix, which produces high yields of liquid products and is easily regenerated through steaming (Olazar et al., 2009). In more recent experiments, pyrolysis has also been performed in the presence of hydrogen, which minimizes the extent of coking as well as the fractional yield of unsaturated compounds (Munir et al., 2018).

The products of pyrolysis of PSW vary depending on the nature and quantity of the feedstock used, as well as the process conditions and reactor used, they can be categorized into three different classes: liquid hydrocarbons (fuels), gaseous hydrocarbons and char. The liquid products of pyrolysis are the desired products of pyrolysis, and are used as fuel either directly or after blending with motor oil, diesel and gasoline, provide that they maintain desirable that their properties such as boiling point, flash point, fire point, American Petroleum Institute (API) gravity and octane number within the acceptable limits (Sharma et al., 2014). Common classes of liquid products obtained include paraffins (such as butane, heptane and octane), propane, olefins, isoparaffins, and aromatics (Miandad et al., 2017).

Char is the carbonaceous solid material obtained as a by-product after the production of liquid oil and gases. An increase in the fraction of char produced was correlated with an increase in the temperature of pyrolysis (Jung et al., 2010). The composition of char produced is generally dominated by fixed carbon and volatile impurities (Jamradloedluk and Lertsatitthanakorn, 2014). In certain cases, it may possess unique physical characteristics such as pore formation on the surface when co-pyrolysis with biomass is performed (Xue et al., 2015), which allows for its usage as an adsorbent for the purposes of air and water purification.

The gaseous products of pyrolysis primarily consist of lighter hydrocarbons produced through successive successful cracking, along with some volatile impurities from char. Yield of gaseous products from pyrolysis of plastic wastes containing polystyrene (PS) and low density polyethylene (LDPE) is significantly lower than that of the liquid product (Basu, 2010), with an increase in gaseous yield correlated with an increase in temperature (Onwudili et al., 2009). In contrast to this, PVC and PET-based PSW produced high yields (greater than 75 wt%) of gases, due to distinct mechanisms and minimal energy requirement (Çepelioğullar and Pütün, 2013; Fakhrhoseini and Dastanian, 2013). These gaseous products (which include butane, propane, methane and ethane) may be used for energy generation purposes.

Pyrolysis of plastic waste can be carried out in various types of distinctly designed reactors. Batch (Abbas-Abadi et al., 2014) and semi-batch reactors (Owusu et al., 2018) are highly suitable for thermal pyrolysis and may be feasible for use at the household level (Wong et al., 2015). Fixed bed reactors are used to boost the contact time between the plastic and the catalyst in catalytic pyrolysis (Jin et al., 2019), with it being used as a secondary reactor using partially converted feed (Anuar Sharuddin et al., 2016; Vasile et al., 2001), with the common materials used for packing being cement, sand and clay (Obeid et al., 2014).

Fluidized bed reactors improve upon fixed bed reactors by providing much higher contact surface area and a greater extent of mixing, in addition to high rates of heat transfer (Yuan et al., 2014), and low maintenance and catalyst replacement requirements (Iliopoulou et al., 2014). Recent studies have also focused on the use of supercritical water, which serves as a highly effective reaction medium for gasification (Bai et al., 2019), as well as improving dispersion of the formed gaseous products (Bai et al., 2013).

Table 2
Applications of various types of plastic.

Type of plastic material	Characteristics of the plastic material	Uses of the plastic material	Reference
HDPE (High Density Polyethylene)	Solvent resistance, High strength properties polymer	House hold items, ropes, fishing and sport nets and packaging	Omnexus (2019a)
LDPE (Low Density Polyethylene)	Weatherability, good processability, Excellent electrical insulating properties	Packaging industry for pharmaceutical and squeeze bottles, Pipes and Fittings	Omnexus (2019a)
Polypropylene	Good resistance to environmental stress cracking and certain chemicals.	Containers, housewares, furniture, toys	Omnexus (2019b)
Polystyrene	Excellent gamma radiation resistance and Good electrical properties.	Plastic model assembly kits, Plastic cutlery and dinnerware	Omnexus (2019c)
Polycarbonate	Heat-resistant, electrical insulator, Possesses good abrasion resistance	Electrical and telecommunications hardware, Sunglasses	Omnexus (2019d)
Polyvinyl chloride	High dielectric constant, High resistance, Long life span and resistant to all inorganic chemicals	Pipes, building and construction	Omnexus (2019e)
Polyester	Hydrophobic, high tenacity and durable	Fibre, carpets, filters, synthetic artery replacements	Kristin Boekhoff (1996)
PET (Polyethylene terephthalate)	Light weight, Versatile polymer, Transparent, Good resistance to certain organics	Bottles, tapes and food packaging applications	Omnexus (2019f)

The factor that has the most significant impact on a pyrolysis reaction involving plastic waste is temperature, with the nature of pyrolysis as an endothermic process leading to increased rates and conversion (Chin et al., 2014), as well as design considerations for extreme operating conditions (Al-Salem et al., 2017). High temperatures have also been found to be favourable to cyclization reactions among the products (Mastral et al., 2002) and unfavourable to the yield of waxes (Singh and Ruj, 2016). Residence time also has a significant impact on the products, with increased residence time correlated with an increase in the fraction of linear hydrocarbon products (Wong et al., 2015) and in the conversion rate (Andel et al., 2009). Pyrolysis of plastic waste can also be conducted alongside biomass, with a wide variety of synergistic effects reported that affect the nature and yield of the products, such as a reduction in formation of tar (Jin et al., 2019) and in the liquid yield (Miandad et al., 2017). Microwave pyrolysis is another technique that has received attention, involving the inducing of degradation of polymeric molecules through high intensity microwaves that increase the surface temperature of the molecules (Undri et al., 2014).

In the pyrolysis of plastic waste, the plastic material is converted into a fuel that is composed of a mixture of hydrocarbons. The obtained fuel produces carbon dioxide upon its combustion which requires efficient carbon capture and storage to avoid a net positive carbon emission. The production of other greenhouse gases like methane must also be taken into account when a process is to be considered for installation. Proper treatment of greenhouse gases is expensive, but will reduce the environmental impact of the process.

The products produced are done in a sustainable fashion and promote the sustainable model of development. The economic aspect of cogeneration can also be evaluated while the product is discussed. Pyrolysis occurs at high temperature and pressure and the energy needed to be supplied for these conditions to be met is large. The process is therefore highly energy-dependent in nature. In the pyrolysis of plastic, a lot of energy is spent in maintaining process conditions for it to be converted into oil. The concept of durability cannot be applied to the pyrolysis of plastic waste, as the fuel obtained from the pyrolysis is used immediately. Technical difficulties that can be encountered in the process of pyrolysis include the proper setting up of conditions, design of an efficient reactor, addition of catalyst and packing in the catalyst.

During the pyrolysis of LDPE, the effect of using reflux was reflected in energy consumption based on the product composition. The theoretical energy consumption, by a study, for pyrolysis of 20 g LDPE varied from 20.71 kJ for a low reflux rate to 21.45 kJ for higher reflux rates. The same study recorded that 2.5 kg PE waste requires 3.32 MJ for the complete primary cracking and vaporization of the plastic (Engineering, 2010). Diesel oil prepared from waste plastics in Southeast Asia has been shown to have an energy recovery of 54% (Anene et al., 2018). A study showed the potential energy that can be recovered based on the pyrolysis of 2189 MT/day of pure non-recyclable plastic without the addition of polystyrene is around 7.2×10^{12} Btu (Anuar Sharuddin et al., 2017). Another study showed that nearly 70% of the original plastic weight can potentially be converted into a fuel source (Alston et al., 2011).

4.4. Liquefaction

Hydrothermal liquefaction has been a long-serving technique for the conversion of biomass, predominantly from algal origin, to bio-oil. It involves the conversion of cellular material to a high value liquid fuel. The technology has been modified in order to incorporate waste plastics and is particularly attractive due to the possibility of recovering plastic for reuse alongside liquid fuel (Prawisudha et al., 2012). Typically, waste plastic is liquefied in the presence of a form of biomass in a process termed co-liquefaction. Liquefaction of biomass, in most cases, results in better distribution of elements among the products when compared to other waste to value methods. A higher proportion of carbon in the products logically leads to superior fuel performance (Yang et al., 2016). It is important to note that plastics can be liquefied in the absence of biomass but this technique is not as common as co-liquefaction. For any liquefaction process, the selection of catalyst is pivotal and goes a long way in determining the efficiency of the process. In most cases, heterogeneous catalysts are utilized for the process of liquefaction in order to minimize the possibility of corrosion and to improve the interactions involved in the reaction (Xu et al., 2018).

The working of a hydrothermal liquefaction system can be broken down to three steps – depolymerization, disassociation and recombination. The incorporation of a solvent and/or catalyst and the presence of high temperature and pressure conditions results in the depolymerization of the three primary compounds present in biomass into smaller molecules such as proteins, small carbohydrates and amino acids (Cai et al., 2017). The smaller molecules further disassociate to produce elements in their natural form which further recombine to produce product. If the recombination is accompanied by a polymerization reaction, bio-oil is formed.

Further polymerization and degradation of the bio-oil results in the formation of char and coke. The absence of a polymerization step results in the generation of bio-gas (Christensen, 2014). The incorporation of plastics in liquefaction does tend to lower the degree of coke formation. Hence, the incorporation of plastics into liquefaction can be considered to have dual benefits – recycling of waste plastics and enhancement of existing liquefaction products (Zhang et al., 2016).

A study performed on the co-liquefaction of polyethylene with coal succinctly summed up the influence of solvents in co-liquefaction. In the absence of a solvent, yield and conversion were found to be dramatically lower than the values obtained in the presence of a solvent. The hydrogen donation capacity of the solvent was also crucial in determining the efficiency of the process, with tetralin showing significantly better results than methyl-napthalene due to its superior hydrogen donation ability (Pinto et al., 2018). The process can be further improved by using supercritical solvents. The predominant benefits of supercritical solvents lie in the increased solubility and diffusion ability combined with low viscosity and homogeneity (Jin et al., 2018).

The utilization of supercritical water improved the depolymerization of polystyrene to styrene and was found to be positively influenced by temperature increase. Supercritical water was also found to be a better source of hydrogen ions when compared to conventional solvents. Pressure and reaction duration were found to have positive impacts at extents lower than the influence of temperature (Bai et al., 2019). Catalytic requirements include thermal and chemical stability over the course of the reaction, in particular at supercritical conditions and large specific surface area in order to maximize the reaction.

Liquefaction of plastic can be done both in the absence and in the presence of accompanying biomass. The liquefaction of plastic in the presence of biomass is referred to as co-liquefaction and relies on the synergistic interactions between the chosen biomass and waste plastic for enhanced yield. Examples of plastics liquefied through co-liquefaction include high density polyethylene (Baloch et al., 2020), nylon-6 (Raikova et al., 2019) and polypropylene (Wu et al., 2017).

It is also possible to liquefy plastics alongside non-algal biomass, as shown by a study involving the liquefaction of nylon-6, polyethylene, polypropylene and polyethylene terephthalate alongside pistachio hulls (Hongthong et al., 2020). High density polyethylene has also been liquefied in the absence of biomass but the reaction was found to produce lower yield than co-liquefaction and was found to be strongly dependent on the nature of catalyst used (Pan et al., 2018).

A more recent development is the introduction of sequential hydrothermal reactor system (SEQHTL) which allows the recovery of other compounds during HTL process and make the process more economically viable when compared to conventional HTL. One of the biggest drawbacks of conventional HTL is the loss of useful compounds like proteins during the formation of bio-crude. The high temperatures involved result in the destruction of the molecular integrity of valuable components that can be viewed as co-products (Gu et al., 2020). This problem is averted in a SEQHTL system wherein different compounds are extracted individually. Typically, SEQHTL comprises of two reactors in series with the first reactor at lower temperature (140 °C–180 °C) and the second at moderate (220 °C–280 °C) temperature respectively.

The temperature in the first reactor ensures the rupture of biomass cell walls but prevents the damage of proteins present in the biomass. However, the proteins and other co-products such as pigments, lipids and amino acids get released from the cell wall in this reactor and can be extracted. The products from the first reactor act as the inlet for the second. The relatively higher temperature in the second reactor accelerates the production of bio-oil. At lower temperatures, the separation of co-products is higher and the relatively lower conversion into bio-oil is offset by the incorporation of multiple stages (Miao et al., 2012). However, more study is required in this field in order to fine tune the reaction conditions in order to optimize the product formation. While still young, SEQHTL holds immense promise as a solution for the treatment of both plastic and biological waste.

Liquefaction has been found to need large quantities of water which can be considered as a disadvantage. The process of liquefaction is also conducted at high temperatures and is therefore highly energy-intensive. HTL produces negligible amount of carbon foot print, which is a major advantage of this process. Anaerobic digestion of plastic waste forms methane, a greenhouse gas. However the quantity of methane produced is low. Hence the production of greenhouse gases is extremely low.

4.5. Road construction and tar

Tar refers to a mixture of organic compounds with varying structures and composition. Tar is obtained in considerable quantities during the co-gasification or co-pyrolysis of waste plastics with other materials such as heavy metals. The highly condensable nature of the organic components present in tar makes its presence an unenviable prospect in gas-producing plants, primarily due to its propensity to cause a slagging and inhibit catalysts (Arena et al., 2009). While tar has an undesired effect in gas-producing plants, it is used extensively in other industries and is a value-adding component. It is used in the treatment of plant and human diseases and finds widespread use in the coating industry (Kurt and Isik, 2012).

The production of tar from the gasification or pyrolysis of plastics is a method that has received increased attention in the recent past, with the process acting as an environmental-friendly alternative to the conventional methods of tar production from trees and fossil fuels. In essence, the process involves the gasification of waste plastics to obtain a condensed liquid as a by-product along with fuel gases. The subsequent separation of the condensed liquid results in the production of tar which can then be processed and utilized (Kato et al., 2003). Processes with sound fundamental engineering principles should aim to reduce the amount of tar present in the fuel gas, thereby increasing the amount of tar that can be extracted from the condensed liquid. Besides the production of a highly valuable by-product, the removal of tar from fuel gases also significantly reduces the operating and maintenance costs.

The process typically involves the gasification of plastic waste in the presence of a catalyst. Olivine has been demonstrated to yield good results when acting as a catalyst, with its cheap and inherent eco-friendly nature acting as an additional benefit. The utilization of a fluidized bed also significantly enhances the rates of heat and mass transfer, improving the conversion and rate of reaction. However, the production of carbon monoxide acts as a deterrent to the functioning of the catalyst and must be monitored (Mastellone and Arena, 2008). Along similar lines, activated carbon has also been shown to be an effective catalyst in the removal of tar from the fuel gases sourced from waste plastics. The enhanced surface area of the catalyst has shown tangible benefits to the reaction. The catalyst also exhibited excellent regeneration properties and regeneration was shown to be possible using a variety of agents (Jeong et al., 2019).

Olivine and activated carbon have also been used in conjunction with each other to yield commendable results, with the two catalysts acting complementary to one another. The proportion of tar in the fuel gas significantly reduced, thereby allowing tar to be isolated in liquid form as a by-product (Cho et al., 2013a). Similarly, calcined dolomite and activated carbon have also proven to be an effective combination in the minimization of tar in fuel gases (Cho et al., 2013b).

An increase in the conversion of waste plastic to liquid tar can be achieved by the utilization of lignite-plastic admixture at higher temperatures. The tar production was found to be a strong function of reaction conditions and the heating rate. A free radical mechanism was suggested and found to fit the products generated (Qian et al., 2014). Additionally, the conversion of waste plastic to tar does not necessarily require high-grade fuels that will otherwise find use in everyday or industrial purposes. Gasification has been shown to be possible alongside low-quality coal to yield tar that can be utilized for practical purposes. Low-density polyethylene and polypropylene, in particular, yielded appreciable quantities of tar when used with low-grade coal derived from North-East India (Saha et al., 2018). Polycarbonate and acrylonitrile butadiene styrene have also been utilized as effective waste plastic raw materials for the production of tar through pyrolysis. The tar production was found to appreciably increase with temperate until a critical value and then decrease thereon. The production of tar, in this case, has been attributed to the presence of benzene rings in the structures of the raw materials (Nedjalkov et al., 2017).

The most common application of liquid tar is in road laying. In a vast majority of countries, particularly developing ones, roads consist of a base of bitumen and subsequent layers on top. With time, these layers get compacted and obtain a strong and stable structure. These layers gradually degrade with time and are replaced. The utilization of waste plastics to coat bitumen is a technique that has been on the end of a surge in interest in the recent past. The benefits offered are two-fold: the non-biodegradable plastics can be disposed of in an efficient manner while the roads with plastics incorporated have shown superior performance compared to conventional tar roads (Anand et al., 2017).

Studies have shown that nearly one tonne of waste plastic gets utilized in laying a kilometer of roads, thereby solving the complex problem of waste disposal and subsequent emissions (Vasudevan et al., 2012). The incorporation of waste plastics in the laying of roads was found to save nearly ₹40,000/kilometer of road laid (Bondre et al., 2015). India is the most common exponents of this strategy, with other countries such as the Netherlands and the United Kingdom following them. The utilization of waste plastics in road making is also gaining prominence in other developing countries such as Ghana and Malaysia (Sasidharan et al., 2019).

Generally, waste plastic is blended with bitumen at high temperatures approaching 170 °C followed by cooling. Prior to blending, the waste plastic is shredded to sizes that enable the passing of the shredded plastic through sieves of sizes in the millimeter range. The process of shredding results in enhanced plastic surface area and as a consequence, in greater bonding between the plastic pieces and bitumen. The cooling step, in particular, is important as it is the largest contributor to the strength of the roads. Road-laying is carried out at temperatures around 120 °C. One study has shown the strength of the road to be directly correlated to the amount of plastic present, with an additional economic benefit of reduced bitumen requirements (Yadav et al., 2017).

The incorporation of plastic results in an elevated melting point of bitumen and superior flexibility. Superior rainwater tolerance has also been observed in roads with plastic incorporated in them. Furthermore, the prospect of the utilization of a mixed plastic feed also reduces the potential costs involved in waste plastic segregation. Superior ultra-violet resistance and longevity of plastic roads are also additional benefits. The increase in stiffness upon the addition of waste plastics to bitumen is down to a progressive enhancement in the forces of attraction between the bitumen and waste plastic with time. Additionally, the use of oxidizing and linking agents also further enhanced the bonding forces (Jafar, 2016).

The incorporation of waste plastics in bitumen to produce higher-quality roads has been explored in literature. Polyvinyl chloride (PVC) has been utilized in this regard due to its use in everyday life, predominantly in piping. PVC is often heated after blending with bitumen due to its propensity to release toxic compounds when heated directly. When introduced in proportions of 3% and 5%, the strength and resistance to deformation of the roads were found to be superior to the properties of typical bituminous roads.

The modified road was also found to be capable of handling higher loads for longer durations (Behl et al., 2014). Mixtures of HDPE, PET and PE have also been successfully used in the laying of modified roads and pavements. The three plastics are most commonly found in the packaging of foods, carry-bags, and bottles and are the most frequently encountered pollutants in waste handling. In most cases, the term “waste plastics” refers to a mixture of the above four due to their applications in day-to-day life.

The use of plastic has shown an improvement in the performance of the roads as roads are less susceptible to pothole formation (Jan et al., 2018). It has also been shown that the roads made using plastic can withstand heavy traffic and are more durable than flexible pavements. The penetration ability of bitumen reduces with the increase in plastic material in the mixture (Anand et al., 2017). According to a study by a company from the Netherlands, plastic roads were estimated to have a minimum life of 50 years and a maximum of about thrice the life of conventional roads (Urbiztondo and Mirada, 2014). Jambulingam Street, located in Chennai, Tamil Nadu, India is one of the first roads to be made from plastic waste, in the year 2002. The road has survived two floods and reasonable traffic over the past fifteen years and is still intact (Sribala Subramania, 2016).

It is important to note that the use of plastic-modified roads is not merely limited to urban regions. Reports have demonstrated the potential of plastic-modified roads in rural regions, with a study finding plastic roads to be a suitable solution in rural areas in India (Sharma et al., 2017). It is important to emphasize this point since the road usage patterns in urban and rural regions are different in nature. It is very encouraging that plastic roads have been found to withstand the high-traffic use of urban areas while not deteriorating in quality under sparser use in rural regions.

Conversion of plastic into tar for road use does not have high energy demands. Energy is spent in the process of the size reduction process of the plastic and the mixing process of the plastic along with the raw materials.

4.6. Concrete

Concrete finds abundant use in construction and consequently acts as a pillar of industrial progress. Utilizing the extraordinarily long life spans of concrete structures is an increasingly common idea utilized both in academic and industrial circles. Recent trends in concrete studies have focused on the incorporation of different materials, with an emphasis on lighter materials, as substitutes for natural aggregates in concrete. The benefits offered by such lightweight aggregates (LWA) in concrete are multi-fold. Incorporation of LWA results in significantly less time and energy expenditure and a tangible decrease in handling and moving costs of concrete also been observed (Güneyisi et al., 2015). However, studies to choose the right materials to incorporate into concrete are ongoing with several materials being scrutinized at present.

The high production cost of LWAs is a commonly observed deterrent (Topçu and Uygunoğlu, 2007). Of the studied materials, waste plastics are particularly attractive due to the benefits offered in multiple fronts, not least due to the economic aspects. Plastics on average, take years to completely decompose and to attain a suitably harmless composition. To circumvent this challenge, the non-biodegradable plastic is “stored” in concrete structures to prevent direct contact with the external environment, thereby minimizing environmental damage (Saikia and de Brito, 2014).

The introduction of plastics into concrete also benefits the concrete structures, with different waste plastics imparting different properties to the plastic – concrete mix. The addition of polyethylene terephthalate (PET) has been demonstrated to improve resistance to sulphuric acid (Janfeshan Araghi et al., 2015), polyolefins improves tensile strength, polyvinyl chloride improves resistance to chlorine (Senhadji et al., 2015) and polyethylene improves thermal resistance (Ali et al., 2018). Other waste plastics such as polystyrene (Kaya and Kar, 2016), polycarbonate (De la Colina Martínez et al., 2019), polyurethane (Şimşek and Uygunoğlu, 2018), low density polyethylene (Srimanikandan and Sreenath, 2017) and high density polyethylene (Pešić et al., 2016) have also been reported in literature as suitable options for plastic – concrete mixes.

In a study, it was reported that the compressive strength of concrete that was cured using sulphuric acid was higher when 11% of plastic aggregates were used (Ramesan et al., 2015). In the mixing of plastic waste with concrete, it must be ensured that the ratio is not altered, to not affect the properties and setting time of the concrete. The energy requirements in the process are very similar to that of road construction.

The overview of all the six processes explained in this section is mentioned in Fig. 3.

5. Assessment of methods and development of the EEE index

5.1. Requirement for the EEE index

In order to fully understand the holistic nature of any process, it is important to consider different parameters. These parameters can broadly be divided into three categories – environmental, energy and economic parameters. To this end, a multi-dimensional analysis of the disposal techniques is necessary in order to fully evaluate different waste disposal techniques. The EEE index was calculated keeping this fact in mind using a technique of simple averages. While plastic disposal and management is designed to reduce the environmental impact of plastic waste, the techniques used can sometimes lead to unintended harm towards the environment. In order to truly minimize the environmental impact, a process must not only be capable of effectively reducing the plastic waste but also not create unintended negative consequences (Rigamonti et al., 2014).

Along similar lines, it is important to note that certain waste disposal techniques are expensive to carry out due to the technological and manpower requirements. Clearly, not all countries can afford a process that produces a minimal return on investment (Bernardo et al., 2016) and as such, developing countries may prefer inexpensive techniques to expensive techniques that do not produce a great increase in performance (Mwanza and Mbohwa, 2017). The energy efficiency of a process can be understood by analyzing the quantity of energy needed to carry out the process as compared to the energy obtained. As such, a process that requires large amounts of energy may be deemed suitable in scenarios where the technology to recover a proportional amount of energy is available.

5.2. Parameters analyzed in EEE index

5.2.1. CO_2 and CO emissions

Emissions in the form of CO_2 and CO were assessed from the various methods of plastic waste handling, as these the predominant contributors to greenhouse effect. The environmental pollution caused by CO is well documented (US EPA, 2020a); it is therefore important to reduce the carbon emissions from a process in order to categorize a particular method of handling plastic waste as sustainable.

5.2.2. Non-CO_2 and Non-CO greenhouse gases

While CO_2 and CO are the major greenhouse gases, gases such as methane, ethane and other hydrocarbon make a significant impact despite their lower proportion (US EPA, 2020b) and hence need to be accounted for.

5.2.3. Land requirement

Land is a fast vanishing commodity that has an inexhaustible demand. It is thus important to minimize the land needed for a conversion process. However, different plastic treatment methods have different land requirements (Shen et al., 2020). This fact is accounted for in this aspect of analysis.

5.2.4. Land reusability

It is also important to factor in the irreclaimability of a used space. Not all plastic treatment methods have the same impact on the surrounding land (Moharir and Kumar, 2019). For example, it is not possible to reclaim land that has been used in toxic landfills for agricultural purposes.

5.2.5. Quantity and nature of plastics used

A process is more efficient when it has the ability to handle large quantity of feed. This reduces the number of operation cycles to deal with a particular quantity of waste. Another aspect to check is the versatile nature of feed and the ability of a process to handle mixed fee of plastic waste (Wang et al., 2017). This was relatively evaluated among the various techniques as quantity/type of waste plastic use.

5.2.6. Water requirement

Water is perhaps the most important commodity in everyday life, due to the high demand and low supply. As such, it is necessary to minimize the amount of water used in a process. The quantity of water required by a process (Mourshed et al., 2017), and the proportion of water that can be reused in the same process were evaluated in this criterion.

5.2.7. Energy requirement

Energy supply in many places in the world is not consistent. While developed countries have access to uninterrupted energy flow, developing countries struggle to match this. During the evaluation of different techniques, it was seen that certain process were more energy intensive (Anuar Sharuddin et al., 2016) when compared to others. In view of this the energy requirement of a process was thus considered.

5.2.8. Energy economy

Energy can be recovered from the combustion of products, which can either be liquid and gaseous in nature, formed during the waste plastic handling technique (Anuar Sharuddin et al., 2017). This ability to recover expended energy was evaluated as energy economy.

5.2.9. Sustainability of products

Different processing techniques converted plastic waste into suitable products by their operating mechanisms. These products were evaluated on basis of their sustainability. Sustainability was determined by the long term usage of the process and their main products. The guidelines for sustainable development laid by the UN such as improving life on land, affordable and clean energy and sustainable transport were taken into account (United Nations, 2018) while evaluating this criterion.

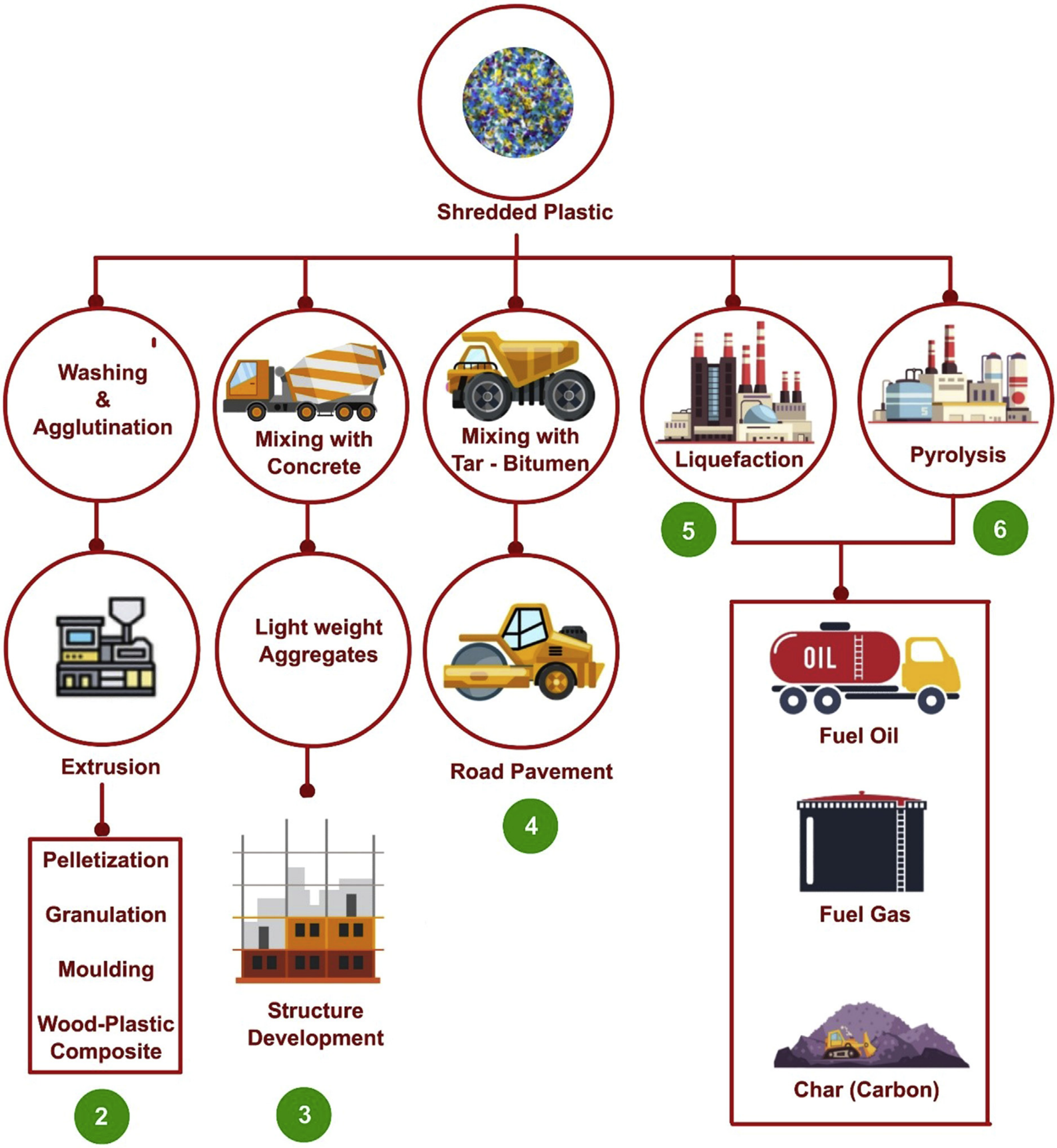

Fig. 3. Overview of Recycling (2), Concrete mixing (3), Tar mixing (4), Liquefaction (5) and Pyrolysis (6) processing streams.

5.2.10. Production of co-generation byproducts

As technology evolves, it has become more important for processes to not only fulfill their primary objectives, but also produce secondary products that can be utilized elsewhere. Apart from the primary products formed in the conversion process, the byproducts and their use was taken into consideration as cogeneration products. Valuable by-products are often used on an industrial level and hence reduce the total costs involved in the waste treatment process. For example co-liquefaction of waste plastic with biomass produced biochar, a highly valued product (Brown et al., 2011).

5.2.11. Cost of a process

Monetary resources and man power requirements are vital for the setting up of an industry. The cost of a process can be viewed as a determining factor for starting any industry. Some processes may not be economically viable due to the costs involved, even if they are environmentally sustainable (Hahladakis and Aljabri, 2019). The various techniques of plastic waste were thus assessed on the cost of operation and maintenance wherever deemed appropriate.

5.2.12. Skilled labor requirement

The requirement of skilled labor is another constraint that is taken into account in the EEE index. This parameter is important to ascertain the technical expertise needed to run a process facility. Skilled workers cost more than unskilled workers and as such, serve to increase the cost of a process.

Table 3
Overall index calculation of various plastic handling processes.

Parameter	Assessment	Landfill	Recycling	Pyrolysis	Liquefaction	Road laying	Concrete
Carbon emissions	Impact	Unfavourable	Neutral	Favourable	Favourable	Favourable	Favourable
	Score	−1	0	1	1	1	1
	Remarks	Carbon emissions from incineration of plastic are high	Emissions from the operation of conversion equipment are moderate	Low levels of carbon emissions, since the process is oxygen-independent (Emissions result only from combustion of fuels)	Low levels of carbon emissions due to absence of oxygen in the products of HTL (Emissions result only from combustion of fuels)	Carbon emissions produced as a result of tar production are primarily due to equipment operation and fuel usage, and are therefore low	Very low carbon emissions which are due to usage of mixer equipment
Land requirement	Impact	Unfavourable	Neutral	Favourable	Favourable	Neutral	Neutral
	Score	−1	0	1	1	0	0
	Remarks	Large amount of land is required for construction of a landfill suitable for handling large quantities of waste	Land required is mainly utilized for construction of recycling plant	Land requirement is very low, with a small amount facilitating setting up of the pyrolysis reactor	Land requirement is low, as small spaces are sufficient for construction of HTL plants	Mixing of plastic with tar requires a moderate amount of land	Mixture of concrete and plastic waste may be conducted in containers of any applicable size depending on the local requirements
Land reusability	Impact	Neutral	N/A	N/A	N/A	Favourable	Favourable
	Score	0	–	–	–	1	1
	Remarks	Buildings can be constructed on land used for landfill creation, but agricultural usage is not possible	–	–		Land can be reused	Land can be reused
Water consumption	Impact	Favourable	Unfavourable	Favourable	Unfavourable	Neutral	Neutral
	Score	1	−1	1	−1	0	0
	Remarks	No water consumption	High levels of water consumption for decontamination and cleaning	Water requirement is minimal (only for cooling purposes)	High amounts of water for usage as the liquefaction medium	Moderate water usage as a mixing medium	Moderate water consumption for dilution and fixing appropriate compositions
Non-CO2 greenhouse gases	Impact	Unfavourable	Favourable	Unfavourable	Favourable	Favourable	Favourable
	Score	−1	1	−1	1	1	1
	Remarks	Landfills generate significant amounts of methane upon decomposition	No emission of non-CO2 greenhouse gases	Methane, ethane and other hydrocarbons predominantly makeup the gaseous products of pyrolysis	Low methane production (only from anaerobic digestion of obtained biomass)	No emission of non-CO2 greenhouse gases	No emission of non-CO2 greenhouse gases
Energy requirement	Impact	Favourable	Neutral	Unfavourable	Unfavourable	Favourable	Favourable
	Score	1	0	−1	−1	1	1
	Remarks	Energy consumption in construction and utilization of landfills is very low (only for equipment and waste transport)	Moderate amount of energy required (for operation of recycling equipment such as cutters and crushers)	High amount of energy is required for maintaining extreme process conditions such as high temperature and pressure	High energy requirement for effective thermal degradation	Energy required for mixing of tar and plastic is very low	Energy required for mixing of concrete and plastic is low
Energy economy/ production	Impact	Unfavourable	Unfavourable	Favourable	Favourable	Unfavourable	Unfavourable
	Score	−1	−1	1	1	−1	−1
	Remarks	Energy expended cannot be recovered	Energy expended cannot be recovered	The products obtained from pyrolysis, which are liquid fuel, gaseous fuels, and char, can all be utilized for energy generation, allowing for recovery	Char and liquid oil are produced as a direct result of liquefaction, both of which can be used for energy generation	Energy expended cannot be recovered	Energy expended cannot be recovered

(*continued on next page*)

Table 3 (*continued*)

Parameter	Assessment	Landfill	Recycling	Pyrolysis	Liquefaction	Road laying	Concrete
Cogeneration products (valuable products besides the primary product)	Impact	Unfavourable	Unfavourable	Favourable	Favourable	Unfavourable	Unfavourable
	Score	−1	−1	1	1	−1	−1
	Remarks	No valuable by-products are obtained	No valuable by-products are obtained	Gaseous hydrocarbons and char are obtained as by-products	Biomass and biochar are obtained as by-products from co-liquefaction of biological waste and plastic waste	No valuable by-products are obtained	No valuable by-products are obtained
Sustainability of product	Impact	Unfavourable	Favourable	Neutral	Neutral	Favourable	Favourable
	Score	−1	1	0	0	1	1
	Remarks	Difficult to maintain landfills in an environmentally and public-friendly manner for a long period of time	Plastic products are converted into other plastic products continually, with the chemical structure of the plastic remaining unchanged	Chemical products of pyrolysis are unlikely to be maintained in their initial form for long	Chemical products of liquefaction are unlikely to be maintained in their initial form for long	Roads constructed using plastic waste for tar production last for long periods of time without damage	Buildings constructed with plastic mixed in the concrete are structurally sound and are not easily damaged
Cost	Impact	Favourable	Unfavourable	Neutral	Neutral	Favourable	Favourable
	Score	1	−1	0	0	1	1
	Remarks	Dumping of waste in landfills is extremely cost effective	Conversion of plastic from one physical structure to another is expensive and the majority of the cost cannot be recovered from sale of the products	Cost of highly sensitive equipment and reactor construction can be offset by production of valuable products	Cost of highly sensitive equipment and high water consumption can be neutralized by production of valuable products	Cost of mixing of plastic in tar is low, and large amounts of tar can be produced	Cost of mixture of plastic in concrete is low
Skilled labor requirement	Impact	Favourable	Favourable	Neutral	Neutral	Favourable	Favourable
	Score	1	1	0	0	1	1
	Remarks	Very little skilled labour requirement (only for supervision purposes)	Skilled labour requirement is very low, since the majority of labour is required for simple tasks such as segregation, cleaning and sanitation	Moderate amount of labour is required for reactor design and supervision	Moderate amount of labour is required for reactor design and supervision	Very low labour requirement (for determination of tar composition)	Very low labour requirement (for determination of concrete composition)
Impact on society/ everyday life	Impact	Unfavourable	Favourable	Favourable	Favourable	Favourable	Favourable
	Score	−1	1	1	1	1	1
	Remarks	Causes the pollution of the soil and water; may lead to spread of pathogenic diseases	Prevents the disposal of harmful plastic waste by converting it into other usable forms	Produces highly valuable products such as liquid and gaseous fuels and char, which allows for rectification of the problem of overdependence on existing fossil fuel reserves	Produces liquid fuels and biochar, which are highly valuable and are used for energy generation	Increases raw material availability for tar production and provides economic benefits	Provides raw material for usage in building construction, eliminating household and local plastic waste generation
Localization	Impact	Favourable	Favourable	Unfavourable	Unfavourable	Neutral	Neutral
	Score	1	1	−1	−1	0	0
	Remarks	Can be easily constructed and performed anywhere on any preferred scale of operation	Can be performed anywhere on any preferred scale of operation	Cannot be easily reproduced due to high capital costs and complexity	Cannot be easily reproduced due to high capital costs and complexity	Can be done on a small scale, but only for privately owned roads	Can be done on a small scale for private buildings
Quantity/Types of waste plastic utilized	Impact	Favourable	Neutral	Neutral	Neutral	Unfavourable	Unfavourable
	Score	1	0	0	0	−1	−1
	Remarks	Can be applied to all types of plastic in any quantity	Quantity of plastic that can be recycled is limited	Large quantities of plastic waste can be pyrolysed only in comparatively small batches	Large quantities of plastic waste can be liquefied only in comparatively small batches	Only some types of plastics can be used and in carefully controlled proportions	Only some types of plastics can be used and in carefully controlled proportions
Net score		−1	1	3	3	6	6
Simple average		−0.07142857143	0.07692307692	0.2307692308	0.2307692308	0.4285714286	0.4285714286
Energy, economy and environmental index (% EEE index)		−7.142857143	7.692307692	23.07692308	23.07692308	42.85714286	42.85714286

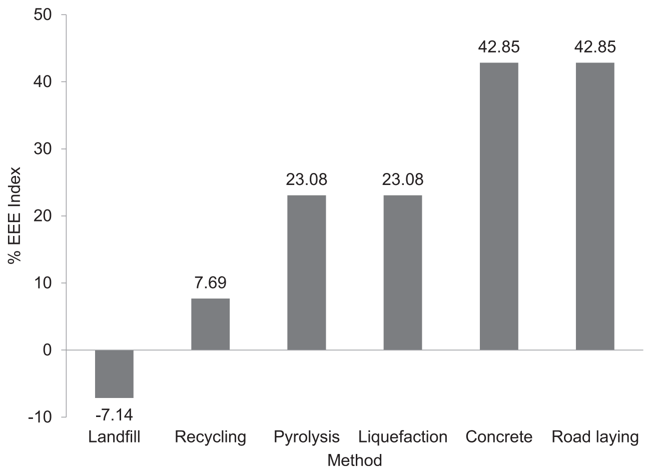

Fig. 4. Graphical representation of IEE index for various plastic conversion processes.

5.2.13. Localization

Localization refers to the possibility of carrying out plastic waste treatment process on a smaller scale. This is particularly important since the implementation of waste treatment on a residential or rural level can lead to more efficient disposal of waste and also produce economic benefits for the region in question (Banu et al., 2020). The establishment of these techniques, depending on their requirements, can be done in an industrial complex or in small localized setups. This ability to implement in plastic conversion techniques in a rural scale was evaluated as localization.

5.2.14. Impact on society

This deals with the unintentional, both positive and negative, consequences of processes on its surroundings. The impact of these processes on everyday lives of surrounding civilians has been taken into account. For example, a process may cause a high degree of sound pollution even though it is highly efficient in nature. Similarly, a process that requires many construction activities does not have a positive impact on society.

5.3. Assumptions made during EEE index development

The 14 parameters described in the previous subsection were used to frame the EEE index. The parameters cover a broad range of aspects that must be considered while selecting a suitable method. During the evaluation of the index, the values of −1, 0 and 1 were chosen in order to achieve a degree of uniformity in the scores. Every parameter was assigned a value of −1, 0 or 1 depending on the nature of favourability. Negative attributes (unfavourable characteristics) were assigned a value of −1 and positive attributes (favourable characteristics) were assigned a value of 1. The value of 0 was assigned in situations for which the characteristic could not be evaluated as favourable or unfavourable. In cases where a parameter was not applicable, the process was not evaluated based on that parameter and that parameter was consequently not considered during the calculation of the index. While this technique has been used to evaluate plastic handling methods in this study, it is important to note that this technique can also be used in other fields.

While it is possible that the extent of two different processes may vary in terms of being positive or negative, the multitude of aspects chosen for this analysis ensures a system of checks and balances. As such, the values chosen are the most suitable in this context in order to minimize confusion and to enable simple understanding of different processes. A comparison on the extent of the positive or negative impact between two selected parameters on a one-on-one basis is possible. However, it is not possible to compare the extent of the impact of one parameter against the extent of the impact of the 13 other parameters.

5.4. Calculation of the EEE index

The index was calculated for each technique using the formulae given below in equations (1) and (2):

$$\textit{Simple average} = \frac{\Sigma\ (\textit{Score assigned for each parameter})}{\textit{Total number of applicable parameters}} \tag{1}$$

$$\textit{EEE Index} = 100 \times \textit{Simple average} \tag{2}$$

Table 3 summarizes the different EEE index scores and the rationale behind the assignment of scores for each parameter.

Based on the study conducted, it can be concluded that the conversion of plastic waste into tar and concrete are the most desirable techniques of waste management in an Indian context. They ensure the cost-efficient disposal of a large amount of plastic waste, help in minimizing pollution and are not particularly energy intensive in nature. On the other end of the scale, recycling is a process that must not be implemented unless other options have been exhausted due to the wide variety of issues associated. The results of the multi-pronged analysis of different techniques have been graphically represented in Fig. 4, in which it can be observed that landfills are a highly inefficient technique of plastic waste handling, necessitating a reduction in their usage for disposal of plastic waste.

6. Conclusion

Analysis of the different plastic waste handling techniques and their merits and demerits was performed using the EEE index. Landfills, which are the predominant method of plastic handling currently, were found to be highly inefficient and inadequate. It registered a negative value on the index due to unfavourable impacts for many of the parameters, being the only such method to do so. As such, the discontinuance of their usage is highly recommended. Analysis of recycling, which is the other dominant contemporary method of plastic handling, found that the merits and demerits neutralized each other almost completely, leading to a net advantage of 1 and a EEE index score of 7.69%. This score indicates that recycling is also an inefficient method, due to significant demerits. Pyrolysis and liquefaction both achieved an index score of 23.08%, due to the significant advantages posed by their generation of valuable by-products such as fuel and char, as well as the possibility of energy recovery. The dependence on fossil fuel sources for energy can be greatly reduced when plastic-to-fuel technologies are employed. However, the negative impact of the high energy requirement and difficulties in localization of the processes are a cause for concern. The most effective methods of plastic handling were found to be the conversion of plastic into tar for construction of roads, and the conversion of plastic into concrete for construction of buildings. Both achieved a EEE index score of 42.85%, due to significant advantages such as the lack of harmful greenhouse gas emissions, the ease of localization and the high sustainability and durability of the produced material and the constructed roads and buildings, the existence of which significantly outweighs demerits such as the inability to recover expended energy. These two methods should therefore be prioritised as alternatives to the existing techniques for future implementations as well as research, owing to their highly sustainable and efficient nature.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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