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Review

Recycling of plastic wastes generated from COVID-19: A comprehensive illustration of type and properties of plastics with remedial options

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HIGHLIGHTS
• COVID-19 paved for huge quantum of plastic wastes.
• Discusses chemistry of polymers in plastic wastes and modes of degradation
• Factors influencing microbial route for degradation assessed
• LCA of plastic polymers generated due to COVID-19 deliberated.

GRAPHICAL ABSTRACT

ABSTRACT

Plastic has contributed enormously to the healthcare sector and towards public health safety during the COVID-19 pandemic. With the frequent usage of plastic-based personal protective equipment (PPEs) (including face masks, gloves, protective body suits, aprons, gowns, face shields, surgical masks, and goggles), by frontline health workers, there has been a tremendous increase in their manufacture and distribution. Different types of plastic polymers are used in the manufacture of this equipment, depending upon their usage. However, since a majority of these plastics are still single-use plastics (SUP), they are not at all eco-friendly and end up generating large quantities of plastic waste. The overview presents the various available and practiced methods in vogue for disposal cum treatment of these highly contaminated plastic wastes. Among the current methods of plastic waste disposal, incineration and landfilling are the most common ones, but both these methods have their negative impacts on the environment. However, since a majority of these plastics are still single-use plastics (SUP), they are not at all eco-friendly and end up generating large quantities of plastic waste. The overview presents the various available and practiced methods in vogue for disposal cum treatment of these highly contaminated plastic wastes. Among the current methods of plastic waste disposal, incineration and landfilling are the most common ones, but both these methods have their negative impacts on the environment. Alongside, numerous methods that can be used to sterilize them before any treatment have been discussed. There are several new sorting technologies, to help produce purer polymers that can be made to undergo thermal or chemical treatments. Microbial degradation is one such novel method that is under the spotlight currently and being studied extensively, because of its ecological advantages, cost-effectiveness, ease of use, and maintenance. In addition to the deliberations on the methods, strategies have been enumerated for combination of different methods, vis-à-vis studying the life cycle assessment towards a more circular economy in handling this menace to protect mankind.

Keywords:
Plastics
Types
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Life cycle assessment

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Contents

1. Introduction ................................................. 3
2. Types of plastic polymers in PPE equipment and medical testing kits used during COVID-19 ................................................. 4
   2.1. Plastics in the confirmatory test kits (RT-PCR) ................................................. 4
   2.2. Plastic polymers and their types ................................................. 5
   2.3. Additives in the polymers ................................................. 7
3. Management of plastics ............................................. 7
   3.1. Current methods of plastic medical waste treatment ............................................. 7
   3.1.1. Landfilling ............................................. 7
   3.1.2. Incineration ............................................. 7
   3.2. Recycling of plastics ............................................. 8
4. Disinfection techniques ............................................. 9
   4.1. Chemical disinfection technique ............................................. 9
   4.2. Heat ............................................. 9
   4.2.1. Using steam or autoclaving ............................................. 10
   4.2.2. Microwave technique ............................................. 10
   4.3. Radiations ............................................. 10
   4.3.1. Ultraviolet (UV) radiation ............................................. 10
   4.3.2. Non-ionizing radiations ............................................. 10
5. Plastic sorting technologies ....................................... 11
6. Thermal processes .............................................. 11
   6.1. Pyrolysis .............................................. 11
   6.1.1. Role of catalysts in pyrolysis .............................................. 12
   6.2. Hydrocracking .............................................. 12
   6.3. Gasification .............................................. 12
7. Chemical recycling and other novel methods ................................... 12
   7.1. Solvolyis .. ........................................... 12
   7.1.1. Hydrolysis ........................................... 12
   7.1.2. Alcoholysis ........................................... 12
   7.2. Mechanochemistry ........................................... 12
   7.3. Dissolution ........................................... 13
   7.4. Ionic Liquids (IL) ........................................... 13
8. Microbial degradation ........................................... 13
   8.1. Factors affecting plastic microbial degradation ........................................... 13
   8.2. Important microorganisms in plastic degradation ........................................... 14
   8.3. Enzymes involved and their action ........................................... 14
9. Life cycle assessment ............................................ 15
10. Circular economy and other alternatives to plastic recycling .......... 16
   10.1. Bioplastics ............................................ 16
   10.2. Design of plastics ............................................ 16
   10.3. Vitrimerisation ............................................ 16
11. Knowledge gaps and perspectives ................................ 17
12. Conclusions .................................................. 18
13. Declaration of competing interest .................................. 18
Acknowledgements ............................................. 18
CRediT authorship contribution statement .................................. 18
References ...................................................... 18

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1. Introduction

Plastics and synthetic polymers have become an inseparable part of our lives in today's world. Every plastic that has been synthesized to date, is still present on earth in some form or the other and it has been a constant environmental problem ever since (Geyer et al., 2017). Adding to the already existing woes, the advent of the COVID-19 pandemic has magnified the difficulties that come with plastic waste management. There is a constant increase in the number of COVID-19 cases, especially with the rise of the second wave in India. This has thrown light on the urgent need for large quantities of PPE (Personal Protective Equipment). Although these PPE contain considerable amounts of plastic, they still seem to be the most affordable and reliable defense against transmission of the virus (Vanapalli et al., 2021). The human-to-human nature of transmission of this virus, through aerosols, has necessitated the need for PPE for health care and front-line workers. There are a larger number of asymptomatic cases being detected, which has made the general public also demand PPE kits, especially disposable single-use face masks, gloves, and face shields without paying any attention to the disposal mechanisms after use. As a result, there has been a steep rise in the manufacture and production of the same across the globe (Adyel, 2020; Prata et al., 2020; Parashar and Hait, 2021; Vanapalli et al., 2021).

At the current rate, enough plastic to fill up one cargo ship every half hour and of the roughly generated 8.3 billion tonnes, 80% is locked up in soil, water and food systems. Approximately 90% of marine plastic pollution is attributed to 10 rivers; most of them are predominantly in Asia. While the lockdowns saw a decline in plastics from 4.6 MT in 2019 to 2.6MT in 2020; however, the demand for SUPs surged. Nearly 9.8MT of medical wastes were generated globally during lockdowns. These wastes would contribute to 4.5% of GHG emissions. By 2050, this is expected to rise to 20% of petroleum consumption and 15% of global carbon budget. Less than 1/10th plastic waste is recycled on a global outlook. End of life processes for plastic waste generated 193 t of GHG in 2019 (Shams et al., 2021), a fraction of 1789 t in emissions generated through the entire lifecycle of plastic including its production. China is responsible for a fifth of plastic waste emanated. Out of 22.1 million tonnes generated in 2019 world over, China contributes to 4.9, whereas, India's contribution is 2.2 million tonnes (Fig. 1).
Looking at the COVID-19 pandemic from the perspective of environmental pollution, health care and public safety in the form of PPE and medical testing kits during this pandemic. There has been a frequent usage of hand sanitizers along with plastic-based PPE, which include face masks, gloves, protective body suits, aprons, gowns, face shields, surgical masks, and goggles by front line health workers to avoid contaminations (Parashar and Hait, 2021). This drastic increase in the usage of PPE (which are generally disposed of after a single use) generates enormous amounts of plastic waste (Patrício Silva et al., 2021). Along with this the protective equipment used by the health care staff as well as infected patients during their transfer to the hospitals or quarantine centres are disposed of after their transport. This plastic problem is further compounded with an increase in the biomedical waste generation from laboratory studies and testing kits, such as disposable plastic components for life support equipment, respirators, and general plastic supplies including syringes, collection swabs, tubes, and much more (Vanapalli et al., 2021).

Looking at the COVID-19 pandemic from the perspective of environmental pollution, it seems to be indirectly contributing to the UN 2030 Sustainable Development Goals, which aim to increase overall health and safety of cities by reducing the greenhouse gas (GHG) emissions, outdoor air pollution, environmental noise level, land and wildlife pressure. However, in reality, it is contrary to environmental sustainability, when we take into consideration the poor indoor air quality, increased consumption of single-use plastics, and a shift in waste management strategies (from segregation to excessive dumping and incineration) (Patrício Silva et al., 2021).

As a result of lockdown and social distancing, there is an increased dependency on online shopping and home delivery of essential items such as pharmaceuticals, food, and groceries (Laguna et al., 2020) which in turn have increased the demand for single-use plastics (SUP) carry bags and plastic for packaging purposes. A new form of behavioral change has also been observed among consumers, like panic buying or stockpiling of food items and groceries which have resulted in a surge in plastic-based packaging in many countries (Parashar and Hait, 2021). Further, the misconception among consumers, that single-use plastics have a hygienic superiority over other alternatives, has shifted their choices in favor of plastic packaging. This belief has thus led to an increase in the use and disposal of plastics even for non-medical applications. Along with this, plastic packaging with SUP also seems to be a cheaper and more convenient option in these economically adverse times for both manufacturers and producers (Guillard et al., 2018). This dominance of SUP packaging in e-commerce leads to the accumulation of plastic waste comprising of thin films, foam, and multi-layered plastics, all of which have very low recyclability. Although this new shift in lifestyle has undermined the public value of plastics, it has highlighted our vulnerabilities to increased pollution levels. As the pandemic situation degrades, leading to an even more dangerous second wave, and further third wave, and so on, we are slowly realizing our increased dependency on plastics at the expense of our environment. This has pushed us deeper into the grave of plastic waste pollution, which we have already been struggling to overcome, in the past few decades (Vanapalli et al., 2021).

As a reaction to the ongoing pandemic that has created fear among the general public in terms of hygiene, many countries have very conveniently, either postponed or lifted the existing permanent bans on single-use plastic (SUPs). This removal of restrictions on single-use plastics will result in a further increase in waste plastic bags and bring back the use and throw culture (SUPs). This removal of restrictions on single-use plastics will result in a further increase in waste plastic bags and bring back the use and throw culture among the consumers, causing a shift in their sustainable lifestyle. Even without any scientifically proven evidence of reduced risk of transmission from single-use plastic bags, when the government allows the removal of such restrictions, it encourages the people’s baseless beliefs that plastic is a more hygienic material when compared to other alternatives. As a result, this belief has increased the usage of disposable plastic products even for non-medical applications. However, on the contrary, coronavirus is known to survive on plastic surfaces for up to three days, which is longer than other generally used packaging materials such as paper (3 h), cardboard (1 day), and cloth (2 days) (Vanapalli et al., 2021).

The demand for PPE has only been increasing drastically, since the beginning of the coronavirus in 2020 (Burki, 2020). In the past few months, with the rise of the second and third waves, especially in India, the demand has only peaked higher. For instance, according to the estimations made in

![Fig. 1. Classification of processing methods for waste plastics world over.](image-url)
2020, a monthly supply of 129 billion face masks and 65 billion gloves would be required to protect citizens worldwide (Prata et al., 2020; Roberts et al., 2022). The WHO had also made its evaluation of the supplies that would be required by frontline workers alone, to deal with the viral transmissions, and according to those estimations, 89 million face masks, 76 million gloves, 30 million gowns, and 1.6 million goggles along with 2.9 million hand sanitisers would be required as part of safety measures (Aragaw and Mekonnen, 2021). As the number of cases has only been rising day by day, the estimated increase in the supply chain of medical safety products by WHO, is found to be about 40% per month worldwide (Boix Rodríguez et al., 2021). Further, the CAGR for the production of PPE has been expected to show a sharp rise of around 20% from 2020- to 2025 (Parashar and Hait, 2021).

The management of plastic waste, in general, was already a major environmental issue, even before the COVID-19 pandemic, because of the rising concerns about pollution in the terrestrial and marine ecosystems (Mallick et al., 2021). In addition, these volumes of plastic waste that are being generated and will be generated in the future by the COVID-19 pandemic is a big threat to the waste management system. Used medical plastic products are mostly contaminated with pathogens and must be treated as hazardous waste. Medical waste from hospitals especially has a higher chance of being contaminated and therefore it must be destroyed completely, to avoid the survival of any residual pathogens. All healthcare centres always have closely attached treatment facilities that are designed to handle a predicted steady flow and composition of medical waste. The pandemic situation, however, has disrupted this system with its massive amounts of waste generation (Klemel et al., 2020; Rajmohan et al., 2019).

Many countries have adopted different measures to deal with the contaminated waste being produced. In the EU, it is compulsory to double bag all the contaminated waste like face masks, gloves, and tissue (Das et al., 2021). Since the spread of the virus is via aerosols like sputum and nasal excretions, even food containers in countries like Germany, are being treated as hazardous waste. The waste collection system is also separate for all the households which have positive or suspected positive COVID-19 cases. Apart from that, there are many cases of asymptomatic infections, and one cannot be sure that any particular household is free of the risk of infections (Torkashvand et al., 2021). Following these practices in times of such crises is necessary to avoid the spread of infection to a larger population. However, this method of waste collection encourages more use-and-throw culture and increases mixed waste production. This behaviour initiates newer challenges for waste management, as health care takes top priority over other environmental issues (Klemel et al., 2020).

According to the estimations mentioned above, this massive increase in plastic waste that is being generated far exceeds our abilities to treat the waste. If suppression of plastic usage is not a solution, then it becomes very important to start slowly looking for alternative ways to treat the existing as well as accumulating waste (Klemel et al., 2020). We must understand that contrary to popular belief, plastic itself is not the problem. It is the mismanagement and underutilization of plastic as a resource, that makes it harmful to the environment (Abali et al., 2019). Therefore, the complete sterilization of all the infectious waste plastics like masks, gloves and face masks before disposal is very important, especially by the general public, to avoid increasing viral transmissions (Vanapalli et al., 2021).

The rise of the second wave in India has caused an exponential increase in the number of cases of infection. To deal with the same the number of PPE kits and medical testing kits being used has also raised exponentially resulting in enormous amounts of waste generation. Citing very recent data, Mumbai has already generated 50,000 kg waste in the first week of April 2021 as against 39,000 kg daily in March 2021. The data shows that from April 1 to 6, the average daily generation from COVID-19 centers was 1265 kg, which was collected in yellow bags, and municipal solid waste (MSW) was 49,296 kg, collected in black bags. While in 2019, on average, 62.4 t of biomedical waste was being generated per day, this had increased to 90.6 t per day in 2021 (Saxena et al., 2021).

As the restrictions and lockdowns have slowly been lifted, there has been the reopening of various workplaces and the movement of the public has also increased. However, since the viral infection will always persist, we must continue to take precautions. This free movement of the public will imply an increased usage of plastic-based face masks and PPE, further increasing the single-use plastics and generating more waste (Peng et al., 2021). Especially in a country like India, with such a massive population, managing the sharp rise in waste products will be a big challenge. To deal with one pandemic we cannot create a much larger problem for ourselves which will end up putting our entire planet’s future at stake. It is high time; we begin to consider and implement all possible eco-friendly and greener methods that encourage a circular economy, even in the middle of a pandemic (Vanapalli et al., 2021).

This review encompasses the various types of plastic polymers available in COVID-19 related wastes, their chemistry, current treatment options to recycle such polymers, and possible microbial degradation options to recycle them. Alongside this, the implementation of a circular economy methodology and life cycle assessment for such plastics has been evaluated, with knowledge gaps depicted.

2. Types of plastic polymers in PPE equipment and medical testing kits used during COVID-19

Plastic polymers have an excellent strength-to-weight ratio; they are durable and extremely versatile in their applications. Some unique properties such as adaptability, sterile nature, cost-effectiveness, ease of use, utility in new applications and solutions, make plastics irreplaceable in the healthcare sector (Parashar and Hait, 2021). To date, there is no other material that shows the same amount of utility or has the same level of economic viability as that of medical-grade plastics (Gadhave et al., 2020). There is an infinite number of medical applications for plastics at present and they will continue to be a part of the field even in the future (Haque et al., 2021a, 2021b). Trying to completely get rid of plastics is inevitable, therefore, it is important for the government and regulators to strictly implement the correct recycling and disposal practices to avoid problems of excessive waste production (Peng et al., 2021).

Owing to all these aforesaid properties, plastic polymers such as polyurethane (PU), polypropylene (PP), polycarbonate (PC), low-density polyethylene (LDPE), polyvinyl chloride (PVC), poly styrene (PS), polyethylene terephthalate (PET) are all widely used in different PPEs (Arikan and Ozsoy, 2015), as shown in Fig. 2. Polymers used in waste packaging bags are mainly high-density polyethylene (HDPE) and low-density polyethylene (LDPE). Among all the polymers mentioned, PS and LDPE are very rarely recycled polymers, PET and HDPE are widely recycled, and PVC and PP and often not recycled at all (Klemel et al., 2020; Parashar and Hait, 2021). The distribution of various types of polymers among plastics used in COVID-19 is shown in Fig. 3. Facial masks and a majority of the medical protective equipment including surgical gowns, surgical caps, gloves, isolation gowns, surgical N95 masks, shoe covers wound dressings, plasters (Karim et al., 2020) and all are fabricated via a method called melt blowing technique with non-woven fabric (Gupta and Edwards, 2019; O’Dowd et al., 2020).

As described this method uses thin micro and nanofibers that tend to be released when the material is finally allowed to degrade. Different plastic polymers degrade at different rates depending on their physical and chemical properties (Chamas et al., 2020). Since face surgical masks are used by medical professionals and the general public alike, they are a major component of the medical waste in this pandemic. Since these face masks, as explained earlier are produced using melt blowing technique, they could become a major source of micro-plastics (De-la-Torre and Aragaw, 2021). Microplastics accumulate in the environment and pose a higher chance of polluting the environment (Horton and Barnes, 2020; Vanapalli et al., 2021) than the original intact plastic which can be recycled.

Due to their small size and weight, they cannot settle in one place, making it difficult for any natural degradation method to work on them (Chamas et al., 2020). As they remain in the ecosystem in this manner for a long time, they are ingested by organisms, leading to their transfer among different species and their further retention in the food chain.
Their smaller size also increases their surface area, allowing them to easily absorb toxic pollutants, heavy metals, and drug residues (Turner and Filella, 2021). Along with the microplastics when these substances enter the body of organisms, they lead to biological and chemical toxicity in them, and over time it will also be toxic to humans (Liu et al., 2021). The different PPEs and the polymers used in them are described in Table 1.

2.1. Plastics in the confirmatory test kits (RT-PCR)

According to a report from 2020, around 22 kg of plastic waste is generated for every 1000 coronavirus tests using the RT-PCR technique (Parashar and Hait, 2021). If we extrapolate that data there is a generation of around 14.5 tons of plastic waste per day. This is in addition to 609 tons per day, of normal biomedical plastic waste and 101 tons per day of COVID-19 biomedical plastic waste that is generated, only in India. In 2021 with the second wave and third wave, there is an enormous increase in testing numbers globally and hence, the volume of plastic waste generated is much higher (Celis et al., 2021).

The most common way of disposing of bio-hazardous plastic waste from the testing kits, which comprise about 97% of the total plastic residue, is through incineration. The polymer composition in these plastic residues from all the components of the testing kits correspond to approximately 91.5% of polypropylene, 8.49% polyester, and 0.01% polyethylene (Roosen et al., 2020). On the contrary, 3.20% of the total plastic waste comprises non-hazardous plastic waste, which is usually sent to landfills. These residues comprise 55.69% of polyethylene, 44.30% of polypropylene, and 0.01% of polyester (Celis et al., 2021).

We need to understand that these testing methods cannot be altered or reduced under any circumstances because these methods help us detect and diagnose the infection before it spreads to a larger population causing more damage to human lives. Thus, the usage of single-use plastics during this pandemic for such purposes becomes necessary (de Sousa, 2021). The plastic waste generated by COVID-19 tests, for instance, can be estimated using the data of the number of tests that have been performed. Since the RT-PCR testing is done by following a standard technique worldwide, it may be much easier to get an estimate of the plastic waste generated. However, many a time such quantifications become incalculable in some cases. For example, although PPE is made of plastic and weighs more than the test kits themselves, there is no source to quantify the amount of PPE being utilized (Bauchner et al., 2020). Further, when it comes to quantifications during such a pandemic, medical plastic residues from COVID-19 tests have no relationship with the population size or the country’s gross domestic product (Celis et al., 2021).

An estimation of plastic waste generated by RT-PCR diagnostic test, by continent has been described in detail in Fig. 4. Similarly, a statistical study from 2020, of the top ten countries with the highest amounts of plastic waste generation has also been depicted in Fig. 5. Further, these statistics however will also vary when we take the second wave and third wave, which has hit many countries, into consideration (Celis et al., 2021).

2.2. Plastic polymers and their types

There are several different polymers utilized in making different varieties of plastics depending on their utilization (Table 1). A majority of plastic polymers are inert/non-reactive (Chamas et al., 2020). However, some polymers are weakened or even dissolved using nonpolar organic solvents.
| Polymer                | Structure         | Properties                  | N95 | Face Shields | Goggle | Glove | Cover-alls | Shoe & Headcover | Gowns | Bio-hazard Bags | Eco-toxicity                                                                                     |
|-----------------------|-------------------|-----------------------------|-----|--------------|--------|-------|------------|-------------------|-------|-----------------|-----------------------------------------------------------------------------------------------|
| Polyethylene Low density (LDPE) | -(CH<sub>2</sub>-CH<sub>2</sub>)<sub>n</sub> | Soft, waxy solid           | +   | +            | +      | +     | +          | +                 |       |                 | Very minimal toxic effects on human health and the environment. Microplastics can cause blockages and also affect aquatic fauna when ingested. |
| Polyethylene High Density (HDPE) | -(CH<sub>2</sub>-CH<sub>2</sub>)<sub>n</sub> | Rigid, Translucent solid   | +   | +            | +      | +     | +          | +                 |       |                 | Can leach nonylphenol, especially when exposed to sunlight, which is an endocrine disruptor. |
| Polypropylene (PP)     | -(CH<sub>2</sub>-CH(CH<sub>3</sub>))<sub>n</sub> | Atactic: soft, elastic solid | +   | +            | +      | +     | +          | +                 |       |                 | can leach plastic additives and has been linked with the causation of occupational asthma. |
| Polypropylene Chloride (PVC) | -(CH<sub>2</sub>-CHCl)<sub>n</sub> | Strong Rigid solid         | +   | +            | +      | +     | +          | +                 |       |                 | most toxic and the most harmful contains bisphenol A (BPA), lead, phthalates, mercury, dioxins and cadmium. Endocrine disruptor, carcinogenic         |
| Polystyrene (PS)       | -(CH<sub>2</sub>-CH(C6H<sub>5</sub>))<sub>n</sub> | Hard, rigid clear solid    | +   | +            | +      | +     | +          | +                 |       |                 | can leach styrene, causes neurotoxic, cytogenic, carcinogenic and hematological effects.          |
| Polyester (PE)         | -(CO(CH<sub>2</sub>)<sub>4</sub>CO-OCH<sub>2</sub>-CH<sub>2</sub>)<sub>n</sub> | High strength and toughness, good abrasion and heat resistance, transparent engineering thermoplastics | +   | +            | +      | +     | +          | +                 |       |                 | Contains BPA, an endocrine disruptor. Affect one's behaviour, immunity, neurological functions and even cardiovascular health. Also, carcinogenic. |
| Polycarbonate (PC)     | Strong, stiff, hard, tough, transparent engineering thermoplastics | +   | +            | +      | +     | +          | +                 |       |                 |                                                                                               |
| Terephthalate (PET)    | High clarity, Good chemical resistance, gas & moisture barrier, Medium rigidity, scratch resistance | +   | +            | +      | +     | +          | +                 |       |                 | Can cause eye and respiratory tract irritation and acute skin rashes. Known to leach antimony trioxide Acetaldehyde and phthalates. Endocrine disruptors damaged the nervous system. |
| Polyvinyl acetate (PVA) | Soft sticky solid, water-soluble, | +   | +            | +      | +     | +          | +                 |       |                 | Not known to have any harmful effects on humans. Not mutagenic. It is known to be biodegradable. |
| Latex (cis-1,4-polyisoprene) | High tensile and elastic strength | +   | +            | +      | +     | +          | +                 |       |                 | Release hydrogen cyanide and styrene on burning which is all poisonous gases and carcinogenic.   |
| Weight of each PPE component | 135 g | 3-4 g | 35-40 | 25 g | 5-6 g | 150 g | 5-10 g | 180 g | 5-8 g |                                                                 |
These differences in the properties of polymers are a result of many different factors such as:

- Functional groups
- The number of monomers present
- Degree of cross-linking/saturation

Plastic polymers can be broadly classified into 2 main categories- thermoplastic and thermoset. Thermoplastics do not have any cross-links and are, therefore, capable of withstanding more heat. This allows them to go into a molten state or soften when heated and once they cool down, they maintain their shape. They can thus, be remolded into shapes and materials to our convenience. They are formed by additional polymerization and contain linear long-chain polymers. They are weak, soft, less brittle, and have a lower molecular weight and are thus easier to be degraded especially by microbes, e.g., polyethylene, polypropylene, polystyrene, polyvinyl chloride (Ouellette and Rawn, 2015).

Thermoset plastics on the other hand are highly cross-linked with covalent bonds, which does not allow them to soften at high temperatures. This makes it hard for them to be re-molded. They are formed by condensation polymerization. They are strong, hard, and brittle and have a higher molecular weight, e.g., polyester, polycarbonate, polyamide, polyurethane (Ouellette and Rawn, 2015).

2.3. Additives in the polymers

Apart from the above-mentioned polymers that are already highly toxic to the environment, many of these plastics has additives, as mentioned in Table 2, that help in improving their properties like flexibility strength or elasticity, anti-fog, anti-scratch, anti-glare, anti-static. All of these additives add to the toxicity of plastics causing a lot of damage to their surroundings when they undergo degradation (Hahladakis et al., 2018; Wiesinger et al., 2021).

The significance of leachable chemicals from microplastics depends on parameters such as the chemical concentration in the parent plastic, their partitioning coefficient, the age and degree of degradation of the microplastic being studied (Halden, 2010; Okunola et al., 2019). For instance, the degree of crystallinity in aged microplastics will be higher, and thus they may have reduced leaching (Lambert et al., 2017).

3. Management of plastics

The appropriate, as well as eco-friendly methods of management of waste generated from the pandemic, is very important. In an attempt to safeguard our health, we must not ignore the future environmental implications of plastic waste generated. For example, even if 1% of the facial masks are disposed of inappropriately, then it would still lead to around 10 million masks polluting the environment every month (Shiferie, 2021). Each face mask approximately weighs 4 g and this would thus be equivalent to around 40,000 kg of plastic into the environment as pollution (Patricio Silva et al., 2021). Further, we do not have information about how these masks are disposed of either, because many common people who do not have enough awareness will end up mixing these masks with the rest of their garbage (Xu and Ren, 2021; Tesfaldet and Ndeh, 2022). This makes it very difficult to segregate the waste and treat it appropriately. The pandemic has completely turned this system upside down with the massive addition of waste which will impact normal operations to a large extent (Parashar and Hatt, 2021).

According to a recent study in Magdalena River, Columbia by Prata et al. (2020), the degradation of non-woven synthetic cloths (PPE), was a major source of the microplastic microfibers found in both, the water and sediment samples. This eventually has harmful effects on the terrestrial as well as aquatic biota (Patricio Silva et al., 2021).

3.1. Current methods of plastic medical waste treatment

Three major waste disposal systems in place for the treatment of medical wastes depending on their hazard level are mechanical recycling, incineration, and landfilling. According to an estimation by the Ellen McArthur Foundation at the global level, the percentage of plastic waste undergoing mechanical waste recycling is only 1%; whereas the rest are either incinerated (25%), dumped into sanitary/unsanitary landfills (40%), or they leak into the environment as a result of mismanagement (19%) (Vanapalli et al., 2021). It has been observed that, at a global level, almost 14,900 tons of plastic residues have been incinerated, and 494 tons of plastic end up in landfills. More than 10 tons of plastic waste is incinerated in most countries (Celis et al., 2021). The COVID-19 pandemic is highly contagious and is present as a contaminant in all the medical as well as municipal solid waste (MSW) being generated. Therefore, incineration and landfilling are potential disposal methods being preferred over recycling (Fig. 6). Both these methods, however, have deteriorating effects on the air, soil, and water quality in the long run. For example, in the United Kingdom, the carbon footprint of MSW incineration is 0.179 t CO2 eq./t and from landfills, it is 0.395 t CO2 eq./t (Jeswani et al., 2013).

3.1.1. Landfilling

Landfilling is one of the most common methods widely used to dispose of many types of mixed wastes in the hope that they will degrade (Abdel-Shafy and Mansour, 2018). Increased levels of greenhouse gases such as CO2 and CH4 are released in significant amounts during the plastic degradation process in these landfills (Royer et al., 2018). Since this degradation process is highly time-consuming, the gases released thereafter also remain in the air for a longer time (Prata et al., 2020; Okunola et al., 2019).

The process of incineration has a greater advantage over landfilling when it comes to energy recovery. Yet, landfilling is comparatively more preferred only from the waste management perspective. A study performed on non-recyclable plastic (Hopewell et al., 2009) showed that the CO2 emissions from landfilling (253 g per kg) are much lesser compared to incineration (673-4605 g per kg). However, a majority of developing and underdeveloped countries still follow the unsanitary dumping of wastes...
without prior treatment. This method leads to massive space constraints, leaching of toxic chemicals, and can also cause open fires to occur in dumps (Eriksson and Finnveden, 2009). It will have the same effect as incineration, releasing large amounts of air pollutants such as dioxins and furans. (Vanapalli et al., 2021).

3.1.2. Incineration

Thermal treatment is yet another method used to treat large medical plastic residues. Thermal treatment is also given more importance because the high temperatures used in thermal treatments ensure the complete disruption of any type of microbial contamination (Błaszczyk and Iciek, 2021). Some of the thermal treatment methods commonly used are incineration, steam treatment (autoclaving), microwave treatment, and plasma treatment. Different types of treatment can be used depending on the type of plastic waste, technical, economic, environmental, and social acceptability of the region. Incineration is done at very high temperatures of 800–1000 °C, along with the recovery of waste heat energy is a very realistic and sensible choice to make in terms of waste disposal (McDonnell, 2009). This method as mentioned will ensure complete removal of contaminants and also release heat energy that can be utilized for other purposes (Klemes et al., 2020). The incineration method continues to be the best choice for the amount of medical plastic waste (>10 t/day), mainly because of its safety reasons. If the volumes of medical waste are lesser (<10 t/day), then other methods such as chemical disinfection or physical disinfection (microwaves or high-temperature steam) are better options (Patricio Silva et al., 2021). The bigger challenge during this pandemic, however, is surpassing the incineration capacity by a huge margin. For instance, during the starting phase of the pandemic in 2020 the highest amount of waste generated in Wuhan, China was 240 tpd (tons per day) which was almost 5 times above the normal incineration capacity of just 49 tpd (Klemes et al., 2020). This will surely have a severe impact on the air quality, leaving no room for the environment to recover (Parashar and Hait, 2021).

The process of incineration, unlike landfilling, has energy recovery. Many developed countries like, Sweden, Denmark and Poland have all been using various modern and advanced technologies such as the “waste to energy” system that works by treating waste and also acts as an air pollution control method. One of the best examples of a country utilizing this method is Sweden, where up to 23% of energy output is recovered from both municipal and industrial waste incineration (Holmgren, 2006).

3.2. Recycling of plastics

Since most plastics are non-biodegradable, the focus should be on reducing the production itself. It is also important to note that, the plastic waste residues from the pandemic must be sterilized before being recycled (Parashar and Hait, 2021).

The process of plastic recycling depends majorly on the purity of the plastic that is being considered. Therefore, many impurities in the form of dust, dirt, additives, inorganic materials, and mixed polymers act as barriers in the pathway of recycling (Klemes et al., 2020). Single stream plastic like PET with the least number of mixed polymers and impurities is easier to recycle (Hopewell et al., 2009). On the contrary, mixed plastic streams, SUPs and multilayer plastics are quite expensive to be recycled and have almost no economic value even after recycling. Some of the common problems faced during mechanical recycling of waste products are polymer cross-

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### Table 2

| Toxic additives/compounds | Plastic types | Public health effects |
|---------------------------|--------------|-----------------------|
| Bisphenol A               | PVC, PC      | Mimics estrogen, ovarian disorder |
| Phthalates                | PC, PVC      | Interferes with testosterone causing problems in sperm motility |
| Persistent Organic Pollutants (POPs) | All plastics | Possible neurological and reproductive damages |
| Dioxins                   | All plastics | Carcinogenic interferes with testosterone |
| Polycyclic aromatic hydrocarbons (PAHs) | All plastics | Development and reproductive toxicity |
| Polychlorinated biphenyls (PCBs) | All plastics | Interferes with thyroid hormone |
| Styrene monomer           | PC           | A carcinogen can form DNA adducts |
| Nonylphenol               | PVC, HDPE, LDPE | Mimics estrogen |
| Vinyl Chloride            | PVC          | Carcinogenic, affects the central nervous system, liver spleen. Irritates eye skin, respiratory system. |
| Acetaldehyde              | PVC, PP      | Damages the nervous system and causes lesions |
| Furans                    | All plastics | Irritates eye and respiratory system, causes asthma |

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Fig. 6. Current Methods in Management of Medical Plastic wastes generated from COVID-19.
contamination, inorganic impurities, additives in the polymer, inappropriate segregation at the source or during the collection of waste, and semi-degraded plastics when they are collected from open dumps (Grigore, 2017; Lange, 2021). All of these factors need to be assessed and some methods must be strictly implemented to ensure the proper recycling.

The recycling process can be categorized into 4 main types:

- Primary (recycling of plastic residues, using mechanical methods, into products that have the same properties as that of parent plastic).
- Secondary (the recycling of plastic residues via, mechanical processing into products with lower properties than the parent plastic polymer).
- Tertiary (use of chemical processes to reduce the polymers to monomers/oligomers so that they can be either re-polymerized to produce fresh plastic products or used for the production of other types of materials).
- Quaternary (energy recovery in any form from the processing of these plastics).

The final products after plastic recycling, may not be as economically valuable as some other recycled materials such as metals or even glass (Hopewell et al., 2009). This is mainly because of the low value of plastics in comparison to metals or glass. Apart from this, technical issues like melting also need to be taken care of during plastic processing methods. These recycling by melting results in the structural weakness in the final products. For instance, two commonly blended polymers, polyethylene, and polypropylene have very limited use after recycling (Löhner et al., 2009).

In the processing of plastic residues through incineration methods, 1 ton of plastic releases around 5–10 tons of CO₂ (Vollmer et al., 2020). When plastic waste is landfilled, less than 2 wt% carbon molecules in the polymers are hardly released even after long intervals (Webb et al., 2013). This reduces the lifecycle of CO₂ to one-third the value obtained by incineration (Abdel-Shafy and Mansour, 2018). Further, after disinfection, some of these materials may still retain its original strength and all the other properties. Thus, they can be reused until the safety standards are met post disinfection.

4. Disinfection techniques

When we talk about the plastic waste generated from the COVID-19 pandemic, we are dealing with “contaminated waste” materials. It is very important to disinfect all these materials before they are recycled or repurposed to prevent the mass spread of the contaminant microbes (Abdel-Shafy and Mansour, 2018). Further after disinfection, some of these materials may still retain its original strength and all the other properties. Thus, they can be reused until the safety standards are met post disinfection.

4.1. Chemical disinfection technique

Chemical disinfection combined with mechanical shredding done before the disinfection has been widely used to pre-treat COVID-19 waste residues. During the mechanical shredding process, the air is passed through high-efficiency particulate air (HEPA) filters to remove any aerosol formation that might be infectious in the successive steps (Liu et al., 2022). The shredded mixture is then mixed with chemical disinfectants and processed in either a closed system or under negative pressure for a stipulated amount of time. This helps the organic substances to be decomposed and inactivates or kills all the infectious microorganisms.

There are several advantages of using chemical disinfection methods - broad-spectrum sterilization, fast action, stable performance, and requirement of low effective concentrations (Rutala and Weber, 2015). There is also no residual hazardous toxins leftover after the process is completed, and this method not only kills all types of microorganisms effectively but also inactivates any spores present (Wang et al., 2020). The contamination of medical equipment and PPE are different depending upon the surroundings in which they have been utilized. Therefore, a sterility assurance level (SLAL) must be established to ensure complete sterilization (Shalaby et al., 2013). Depending on the initial viral activity, the reduction of the microbial load to reach SLAL can be as low as 5 logs, or as high as 12 logs (Lee et al., 2014). However, for any initial load of microorganisms, higher the reduction in concentration post-treatment, the process will be more advantageous and preferred (Jinia et al., 2020).

Tchemicals used in the disinfection of COVID-wastes are classified as chlorine-based and a non-chlorine-based system. A chlorine-based treatment system involves the use of chemicals like NaOCl or Cl₂ that are used as disinfectants. Since chlorine has a high electronegativity, it can easily oxidize peptide links and denatures the proteins, by penetrating the cell layers even at neutral pH (Singh et al., 2012). One of the first chemical disinfectant used was NaOCl which acts by releasing halo acetic acid, chlorinated aromatic compounds, and dioxins. Similarly, Cl₂, a strong biocide being unstable is easily decomposed into salt and mild toxic products. A non-chlorine-based disinfectant like H₂O₂ oxidizes and denatures proteins as well as lipids (Ilyas et al., 2020). Hydrogen peroxide is also a strong oxidizing agent and thus by producing hydroxyl radicals that attack and damage the DNA and other essential cell components (Jinia et al., 2020). High levels of reactivity and no toxic releases associated with these methods make it an advantageous choice.

However, H₂O₂ is not found to be appropriate for linen or cellulose as it degrades the properties of the material (Ilyas et al., 2020; Jinia et al., 2020). To overcome this drawback, vaporized hydrogen peroxide (vH₂O₂) used as a disinfectant showed promising results via degradation of bacteria, and viruses. One of the main advantages of using vH₂O₂ low temperatures is its compatibility with polymeric materials (McEvoy and Rowan, 2019). This has an additional benefit of reduction in processing time to nearly half (e.g., from 10 to 15 h with ethylene to just 6 h with vH₂O₂). It can also be performed at atmospheric pressure or under vacuum conditions. There is no improvement in its compatibility with cellulose-based materials. (McEVoy and Rowan, 2019).

Some other chemicals used are povidone–iodine (0.23%), isopropanol (>70%), ethyl alcohol (>75%), and formaldehyde (>0.7%), known to inactivate the coronavirus (Ilyas et al., 2020; Singh et al., 2020). Formaldehyde alkylates the amino and sulfhydryl groups of proteins and nitrogen atoms of purine bases; whereas glutaraldehyde alkylates the sulfhydryl, hydroxyl, carboxyl, and amino groups (Jinia et al., 2020).

4.2. Heat

Heat is also an excellent disinfecting technique. With an increase in usage and the need for disinfection of N95 masks, few other methods such as heat and radiations have also been successful in destroying the virus. For example, an investigation using dry heat/hot air at 75 °C for 30mins or using ultraviolet radiation at 254 nm and 8watts for 30 mins, have been known to destroy the virus (Chin et al., 2020; Ilyas et al., 2020). However, the level of decontamination and how well it works by penetrating the layers of material and removing the trapped virus is still an unknown phenomenon. There are a few recent studies by Chin et al. (2020), where the stability of the SARS-CoV2 virus was observed at various temperatures. Using a total of 106.8 TCID50 (fifty-per cent Tissue Culture Infective Dose) viruses per ml of viral titer. The SARS-CoV-2 virus was highly stable at 4 °C, as they observed a reduction to 106.1 TCID50 per
mL of viral load, even after 14 days. However, the viruses were inactivated 100% within 5 min at 70 °C. Thus, there exists a lot of scope to heat as a disinfection method for the sterilization of PPE (Chin et al., 2020; Jinia et al., 2020).

4.2.1. Using steam or autoclaving

A very simple and cost-effective sterilization technique, using steam as a disinfection method for FFP2 masks, was demonstrated by a group of researchers at the Delft University of Technology in the Netherlands with dry sterilization and regular steam (van Straten et al., 2021). In the case of steam, the masks were exposed to conditions similar to that in an autoclave (121 °C for 15 min). The results indicated that even as the steam treatment deactivated the virus, the filtration capacity of the mask remained undisturbed (Jinia et al., 2020).

This method of utilizing steam or autoclaving is being seriously considered as a major alternative to incineration. The temperatures are sufficient to destroy all microorganisms including spores and there is no release of toxic chemicals or harmful gases. These systems generally operate at temperatures (121 and 163 °C) under pressure. This treated waste can then be taken to MSW treatment centers where they can be recycled or re-purposed, in the same way as non-infectious waste (Windfeld and Brooks, 2015).

4.2.2. Microwave technique

Microwave technique can be used as an alternative to autoclaving (Lee and Huffman, 1996). The only disadvantage while using microwaves is that no metals must be present in the waste being sterilized (Windfeld and Brooks, 2015). Microwave sterilization can be done in a temperature range of 177–540 °C indicating a possibility of reverse polymerization when the microwaves are applied with high energy in an inert atmosphere. When the electromagnetic waves with a wavelength of 1 mm to 1 m, in the frequency of 100-3000 MHz is applied to any material, then the molecules tend to vibrate and rub against one another causing an increase in the internal energy (Dogan Halkman et al., 2014) and thus maintaining the high temperatures required for disinfection. Some of the advantages of the microwave sterilization technique include limited heat loss, no toxic residues, and the requirement of relatively lower energy and temperatures. According to the "Technical specifications for microwave disinfection, centralized treatment engineering on medical waste" (on trial) published by the Ministry of Ecology and Environment (MEE) of China, microwave disinfection technology was successfully able to achieve the logarithmic value of killing viruses, bacteria parasites, and fungi of ≥ 6 (Wang et al., 2020). This method is also found to be far more helpful when applied to on-site COVID-waste. This type of on-site decontamination not only saves a lot of time but also reduces the risk of transmission during COVID-waste transportation. For the disinfection of COVID-waste, a combination of autoclaving and microwave techniques can be used when the steam used is in a temperature range of 93–177 °C (Ilyas et al., 2020).

4.3. Radiations

4.3.1. Ultraviolet (UV) radiation

UV radiations inhibit the formation of purine dimers that cause single-stranded as well as double-stranded breaks. Single strand breaks are repairable, but double-stranded breaks result in the loss of genetic material. Depending on the particular wavelength of UV radiations used, the effectiveness of sterilization is determined (Rastogi et al., 2010). The maximum absorption of UV radiations for DNA and RNA occurs at 260 nm and thus the exposure of sterilizing material to UV light at around 260 nm is desired for effective sterilization (Jinia et al., 2020).

4.3.2. Non-ionizing radiations

X-rays/gamma radiations are high-energy radiations that damage the DNA of cell by direct energy deposition or by secondary interactions with the surrounding atoms or molecules. In secondary interactions, the radiations interact with the surrounding water molecules producing many hydroxyl free radical groups. The OH− groups, owing to their high electron negativity react with DNA molecules causing up to 90% damage in their chemical and physical structure (Reisz et al., 2014). Both, direct and indirect interaction of the radiations with cells, cause major damage to the double stranded DNA, eventually leading to cell death due to shorter wavelengths and higher energy. The radiation penetrates from the outer Fig. 7. Possible Recycling methods after Sterilization of plastic wastes.
surface to the interior resulting in complete decontamination of the contaminated items. While using ionizing radiation for sterilization, the impact of the radiation on the material of the equipment must also be taken into consideration.

5. Plastic sorting technologies

The plastic solid waste (PSW) generated from COVID-19, although classified as medical hazardous waste, still has a lot of contaminants, like wood, rubber, and metal particles. These contaminants need to be separated from the plastic polymers. In the case of mixed polymers, the individual polymers need to be separated as much as possible before reprocessing them because each of the polymers responds differently to different processing techniques (ScaIenge, 2018). Manual separation of plastics from the contaminants and other polymers is time-consuming and ineffective. Thus, many automatic separation techniques have been studied and put into practice to fasten the process. These sorting techniques rely on differences in the properties of materials, that can be measured such as density, electrostatics, spectral signatures, and wettability (Luciani et al., 2015). For instance, there are many differences in the densities of commercial polymers: PVC (~1.07–1.18 g/cm³) and PET (~1.38–1.49 g/cm³) being denser than polystyrene (~1.07–1.18 g/cm³), polyethylene (~1.04–1.11 g/cm³) and polylefins (~0.91–0.97 g/cm³) (Vadivelu et al., 2016). Since polymer recycling is a complex procedure, there are many advancements in mechanical and optical separation technologies to allow for the correct identification and separation of different material types. Many new modern technologies that have been discovered in recent times have shown promising results in the separation of waste particles as small as 2 mm (Schmaltz et al., 2020). The physical properties of the materials are targeted when mechanical separation systems are used, and for further differentiation of the materials, optical techniques are widely used in combination. To convert the random mixture of different plastics into a highly purified stock, the sorting processes used in recycling plants need to have more effective, accurate, affordable, and efficient irrespective of the type of input waste, origin the non-plastic contaminants. (Rahimi and Garcia, 2017).

Some of the most tested technologies used for plastic sorting/separation are as follows:

- **Magnetic Density Separation (MDS)** – In this method, plastics are separated based on the densities of the constituent polymers. Even with an overlapping or narrow density difference between two plastic polymers, they can be distinguished accurately. This method uses a magnetic mixture of nanometre-sized iron oxide particles suspended in water and separated vertically in a magnetic field. MDS method is a rapid, accurate, and single-step process that effectively sorts HDPE, LDPE and PP. It also segregates other materials such as rubber and metal contaminants (Bakker et al., 2009).

- **Triboelectric separation** (polymer particles are charged using friction, and further, based on the anionic and cationic nature, the particles are separated) (Lyskawinski et al., 2021).

- **Froth Floatation Method** (separation of the plastics based on their wettability. It targets the critical surface tension between molecules and separates them based on hydrophobic or hydrophilic character).

- **Speed acceleration** (delamination of the polymer from other materials, at a very high speed centrifugal/centripetal force).

- **Solvent-based recovery** – based on the solubility of the polymer in organic solvents. This is most effective for polyvinyl chloride, which is dissolvable and thus can be separated from materials insoluble in organic solvents.

- **Hyper-spectral imaging** – combines spatial and spectral analysis of defined solids using in-line sensor technology. 3D imaging is done by examining the material with light in the wavelength of 400-1700 nm (visible and infrared) range (Henriksen et al., 2022).

- **Laser-induced breakdown spectroscopy** (for the evaluation of compositional elements of materials by comparing the in real-time atomic emission spectral data to referenced sources) (Zeng et al., 2021).

**Ultrasound technology** (monitor the separation of plastic waste and also to assess the process quality information) (Maio et al., 2010). There is an imperativeness to shift to a more automated waste segregation system with a combination of artificial intelligence technologies, to increase the safety of labourers working with such wastes. This type of system which makes use of artificial intelligence-powered automated systems to improve the efficiency and the speed of recycling. Since such systems have fewer chances of making errors when compared to manual segregation, the quality and value of the resultant recycled product are always higher (Vanapalli et al., 2021).

There is a lot of research being done on different methodologies that can directly process co-mingled plastic waste. Most plastics are immiscible with one another, thus for plastic waste streams, there is lower phase separation of mixtures and thus the products have very reduced properties. The smallest amounts of contamination, of even one plastic-type with another, can change the properties of the resultant recycled product thereby reducing their potential usage (Klotz et al., 2022). Polymer compatibilizers used are multicomponent polymers, similar to surfactants, and induce specific thermodynamic interaction with immiscible polymers (Ha et al., 1996). They are designed differently based on their functionality, as block polymers, random copolymers, and graft polymers.

6. Thermal processes

Thermal processing, using the principle of waste-2-energy”, is one of the most sustainable solutions at present, to deal with the excessively large amounts of plastic wastes being generated. Thermal processing with energy recovery not only reduces the volumes by 80–95% but also helps in converting the heat energy into some form of useful energy that can be utilized by many other industries (Prata et al., 2020). Pyrolysis is one such method which not only reduces the continuous waste being generated, but also derives profitable energy from the same. Pyrolysis has the upper hand over all thermal treatment methods mainly due to reduced carbon footprint (Thompson et al., 2009; Aragaw and Mekonnen, 2021).

6.1. Pyrolysis

Pyrolysis is one of the ideal methods, especially for those plastic waste feeds that cannot be de-polymerized. Such waste mainly comprises mixed PE/PP/PS possess multi-layer packaging, and are fiber-reinforced composites that cannot be mechanically recycled (Ragaert et al., 2017). In the pyrolysis process, the chemical bonds in plastic polymers are broken using thermal energy in an oxygen-free environment to obtain resultant product (mix of hydrocarbons) and depending on whether a catalyst is used in the process, it is also called catalytic cracking or thermal cracking, however, the process operated under pressure is called liquefaction (Vollmer et al., 2020).

The biggest advantage of this method is that it does not require the separation of the different types of waste plastic before processing and convert them into liquid fuel that can be used by various industries to generate energy for different purposes (Aragaw and Mekonnen, 2021). Applying the process of pyrolysis to plastic wastes at temperatures of around 500 °C can generate large quantities of liquid oil, which can be used in gas turbines, boiler systems, generators, and sterling engines. This method consumes up to ~80 wt % of plastic waste. With the increase in industrialization worldwide, the demand for alternative fuel and energy resources are always high. Since pyrolysis is performed in the absence of oxygen and the fuel contains large amounts of carbon and hydrogen, it does not require further up-grading. Liquid fuels are non-corrosive, non-acidic and have very high calorific values (Jain et al., 2020).

According to various reports, the pyrolysis of plastic wastes at temperatures of 500–650 °C, produces almost 75–80 wt% of liquid oil and waxes (Al-Salem et al., 2017). Especially, plastics such as polypropylene and polyethylene tend to have a very high carbon content (85.5–86.1%). Face masks, made from polypropylene, have high carbon contents, making them an ideal choice for treatment by pyrolysis. On the other hand, goggles, gloves, and face shields are composed of high amounts of PVC that have
6.2. Hydrocracking

Hydro-cracking refers to the thermal breakdown of polymers in the presence of H2 atmosphere and lower reaction temperature thereby decreasing the amount of coke formation by using radicals that block the coke precursors. Both these factors prolong the life of the catalyst during the reaction, thus reducing the amount of catalyst required, and also encourages the production of more saturated products like alkanes in the place of alkenes. These alkanes can be easily broken down into monomers using established steam-cracker technologies, which can be further used to synthesize PP and PE plastic polymers (Franczak, 2021). The use of gases other than hydrogen and nitrogen, are helium, argon, ethylene, propylene, and CO2. For example, in a CO2-rich environment, pyrolysis of PVC reduces tar formation and pyrolysis of PET, the acidity of liquid oil is reduced (Vollmer et al., 2020).

However, we must keep in mind the cost of hydrogen stream, operation set up and thus, the overall investment costs are all quite high (Ragaert et al., 2017).

6.3. Gasification

The thermochemical conversion of carbonaceous compounds like organic waste and even plastic waste, at temperatures of 750–850 °C into a mixture of gases is called gasification (Sikarwar et al., 2016). Some of the commonly produced gas mixtures, also known as syngas, consist of carbon monoxide (CO), hydrogen (H2), carbon dioxide (CO2), methane (CH4), nitrogen (N2), smaller liquids like tar and solid fractions (Bhatia et al., 2021). In gasification, almost any type of solid material can be converted into a gaseous mixture even without any pre-treatment. The chemical process involved in conversion is partial oxidation, which uses oxidizing agents like a mixture of steam and pure oxygen or only oxygen. Air can also be used, instead of pure oxygen, but that will result in lower outputs and is tougher to separate. There is also an increase in gas flow rate, all of which negatively impacts the overall cost of the process. Even from the environmental point of view, this produces a higher amount of noxious gas, which must be carefully controlled. The entire gasification process has many endothermic as well as exothermic processes, but the overall reaction is endothermic. Gasifiers are also used in this process to ensure higher thermal efficiency for further power generation as well as to reduce the harmful emission of gases into the atmosphere. A few impurities like NH3, H2S, NOX, alkali metals, and tars are also produced along with syngas (Ragaert et al., 2017).

7. Chemical recycling and other novel methods

7.1. Solvolysis

Solvolysis is a chemical process, involving depolymerization and many other interchain reactions that result in the production of oligomers and monomers. Solvolysis converts the thermoplastics and thermostets such as polyesters, polyamides, and polyurethanes (Xanthos and Patel, 1998). Unlike pyrolysis, this method uses lower temperatures to selectively recover monomers from polyesters and polyamides. The different solvolysis methods include hydrolysis alcoholsysis, phospholipids, ammonolysis, and aminolysis to cleave ether, ester, and acid amide bonds. Solvolysis allows for re-polymerization and production of plastic with the same quality as original polyethylene plastics. The products produced from solvolysis are mostly monomers that can be further purified, by removing colorants and additives. It also results in addition of conventionally obtained monomers and use them for polymer synthesis (Xanthos and Patel, 1998; Grigore, 2017).

7.1.1. Hydrolysis

Hydrolysis uses water molecules to target the linkage points of the polymers and produce the original raw materials. However, it is observed that under normal conditions, almost all hydrolyzable plastic polymers like polyamides, polyesters, polycarbonates, polyureas, and polyurethanes are resistant to hydrolysis, in presence of acidic or alkaline conditions. For neutral conditions, some other parameters like temperature and pressure were altered (Grigore, 2017).

7.1.2. Alcoholysis

Glycolysis is the breakage of polymers in the presence of glycols such as ethylene glycol or diethylene glycol. Methanolysis is the degradation of polymers in the presence of methanol (Fatima, 2014).

7.2. Mechanochemistry

Mechanical stress on polymers results in homolytic cleavage to form radicals. This method is usually applied to restore plastic properties by crosslinking and cross polymerization. However, this method can also be applied to stimulate depolymerization, without the need for any external heat (Miao et al., 2021), due to generation of heat in the ball impact zone. Mechanical stress can be created in shear reactors or ball mills or even during sonication. The efficiency and success of this technique is directly proportional to the molecular weight (Mw) of the feed material, indicating the mechano-chemical bond scission being limited by the molecular weight of the compound (De Bo, 2020). Only when the Mw of material is above a certain limit, the chemical energy generated by mechanical stress causes the breakdown of the covalent bonds. Mechanochemical treatment can also be used as a pre-treatment of waste before it is passed
to pyrolysis. For example, during pyrolysis, if the halogen impurities or additives are not removed, then they form corrosive and toxic gases as end products. This can be easily avoided if the material is pre-treated by mechanochemical methods. The energy-intensive de-chlorination of PVC and removal of bromine additives from PS can be achieved by the ball milling (Vollmer et al., 2020).

7.3. Dissolution

The process of dissolution is widely used to separate one single polymer from a mixture of polymers usually when they are present as multilayer films (Pappa et al., 2001). The process can thus be used to recover plastic polymers from mixed plastic wastes without any additives. This dissolution method makes use of either a single solvent or a mixture of solvents and an anti-solvent. In this method, the solvent is chosen in such a way that it selectively dissolves only the plastic polymer intended to be recovered. An anti-polymer is then added to this solution, thus precipitating the desired polymer out, for recovery and purification. After the dissolution in a solvent and before precipitation with the antisolvent, all the undissolved materials such as pigments and undesired polymer, gets separated from the polymer mixture. After precipitation, the solvent and antisolvent mixture is separated for another batch. This separation, however, becomes expensive in terms of energy and time if the solvent has a very high boiling point. Thus, we must keep in mind to choose the most economically feasible solvent for this method (Vollmer et al., 2020).

Another important aspect is that any residual solvent leftover in the precipitate will affect the polymer properties. Thus, complete removal of the solvent is necessary, and this becomes easier when the solvent is a supercritical fluid because it easily evaporates with decreased pressure. The extraction of the polymer as a precipitate by dissolution results in the production of crystallized polymer, which must be upgraded to produce virgin grade polymers. Also, the precipitated polymer must undergo the process of extrusion to produce polymer granulates that can be used to manufacture new plastic items by re-stabilization, rebuilding the macromolecular structure, addition of elastomers or fillers, and using compatibilizers on mixed recycled blends (Vollmer et al., 2020).

7.4. Ionic Liquids (IL)

Using ionic liquids is yet another recent approach as a strong solvation agent for polymers. This method has been used commercially, but it does have the disadvantage of high toxicity. The process is merritorius due to various enwrapping factors also in environmental parameters including temperature, pH, the salinity of the environment, water activity, sunlight, and many more. In the same manner, these factors also influence the polymer degrading ability of the microorganisms. Since enzymes attack the chemical bond in the polymers, the chemical and physical properties decide the biodegradability of different polymers (Carr et al., 2020). Mixed Microbial Culture (MMC) inhabiting can efficiently utilize all the different available resources found in their surroundings (Jenkins et al., 2019). Screening in nature for such consortia will help us find alternatives to genetically engineered microbes. Such mixed cultures are also beneficial since they are inexpensive and easy to prepare and maintain, have higher conversion efficiencies and are also the least susceptible to contaminations (Carr et al., 2020).

8. Microbial degradation

Microorganisms have repeatedly proven to be excellent tool that are used to degrade various organic substances. Taking inspiration from this, a lot of research has been done over the years, to isolate and identify microorganisms that can be used for the digestion of plastic polymers (Mohanan et al., 2020). Several studies by various researchers worldwide used microbes as well the degradative enzymes produced to deal with the rising levels of plastic wastes in the environment (Geyer et al., 2017). Plastic polymers apart from having a strong backbone, show high levels of crystallinity and surface hydrophobicity, that prevent their natural breakdown and decomposition. (Carr et al., 2020; Jenkins et al., 2019; Ng et al., 2018). Microorganisms utilizes plastics as the carbon source which are energetically less expensive, and ubiquitously present in the soil environment (Jenkins et al., 2019). Further, even if the availability of plastic as raw material for microbes is abundant (for example, in the marine ecosystem), the high levels of salt in the water may prevent the microbes from acting on the plastic source (Carr et al., 2020). Thus, to search for suitable microbes and extract the relevant enzymes from them we must isolate the different microbes from different species and study their degradation under different conditions of pH, temperature, salt, etc. (Lear et al., 2021).

Several studies in recent years have focused on the ability of different microorganisms and their enzymes to degrade synthetic plastics. Even though there are several reviews regarding this topic, almost all of them seem to focus on single streams of plastic polymers like PE/PS/PP/PET/PUR, etc. (Ru et al., 2020). Singh and Gupta (2014) isolated 12 LDPE digesting soil fungi and bacterial strains (Arthrobacter, Micrococcus, Pseudomonas, Streptomyces, Corynebacterium, and Rhodococcus) for degrading the ester bond present in polyestersSeveral bacterial species belonging to the Bacillus genera (Venkatesh et al., 2021) including B. cereus, B. gothelioli, Bacillus sp. Strain 27, B. subtilis, and B. pumilus M27, have shown biodegrading ability. Some other species of fungi and bacteria showing biodegrading activity (Zeemat et al., 2021) included Rhodococcus sp. Strain 36, Aspergillus clavatus strain JASK1, Kocuria palustris M16, Citrobacter seddikii, Alcaligenes sp. and Brevundimonas diminuta (Ajith et al., 2020). According to few studies, the heterotrophic bacteria may be stimulated to digest polymers by the release of dissolved organic carbon from plastic materials (Ontha and Sharief, 2021). In all the cases, the digestion of polymers by microorganisms is caused by enzymes, either externally or internally, that were able to break the carbon bonds in polymers (Ajith et al., 2020). It has also been observed that bio-degradation pathways are linked to "chemical familiarity", where the enzymes break the glycosidic, amide, and ester bonds (Vollmer et al., 2020). The degradation of several plastic polymers by microbial enzymes was reviewed by Wei and Zimmermann (2017) in Plastic Microbial Bio-degradation Database (PMBD). This database contains a list of many microorganisms and their relationship with different plastic polymers. The database also provides information about 79 specific genes that are supposedly related to bio-degradation. Recombinant DNA technologies and tools have been widely used to improve the expression of the specific genes involved in the plastic degradation process. However, these recombinant species must not be released into nature without carefully assessing the risks it poses, as it could become potentially overpowering (Carr et al., 2020). Mixed Microbial Culture (MMC) inhabiting can efficiently utilize all the different available resources found in their surroundings (Jenkins et al., 2019). Screening in nature for such consortia will help us find alternatives to genetically engineered microbes. Such mixed cultures are also beneficial since they are inexpensive and easy to prepare and maintain, have higher conversion efficiencies and are also the least susceptible to contaminations (Carr et al., 2020).

8.1. Factors affecting plastic microbial degradation

The growth of all microorganisms is strongly influenced by various environmental parameters including temperature, pH, the salinity of the growth media, humidity in the air, amount of oxygen, atmospheric pressure, water activity, sunlight, and many more. In the same manner, these factors also influence the polymer degrading ability of the microorganisms. Since enzymes attack the chemical bond in the polymers, the chemical and physical properties decide the biodegradability of different polymers (Kale et al., 2015). Some of these important factors are discussed below.

- Molecular weight (Mw) - has a strong influence because lower compounds with lower molecular weight are more easily degradable by a larger number of microorganisms, and thus lower Mw is favored.
- Melting Temperature (Tm) – higher the melting point of the polymer, the
lower is the degrading ability.

• Time - with increased time the plastic polymers become stronger and decreases the efficacy of enzyme biodegradability.

• Structural properties like modulus of elasticity and crystallinity of polymers also control the polymer biodegradability.

• Presence of stabilizers, antioxidants, and additives further slowed down the rate of degradation as their toxicity affects microbial growth.

Apart from all these factors some structural parameters such as the presence of branching or linearity in polymers, the type of chemical bonds like amide/ester/glycosidic, etc., the physical form of the polymers (fibres, pellets films, powdered form), decide the surface area available for microbial growth, and further the biodegradability. Keeping all these factors in mind, while screening for suitable microbes, is very important (Kale et al., 2015).

8.2. Important microorganisms in plastic degradation

Microorganisms belonging to the Pseudomonas genera are very well known for their ability to degrade most types of plastic polymers as well as their monomers. Pseudomonas sp. has been mostly been studied for its ability to degrade hydrocarbons and other hydrophobic polymers, but most naturally found isolates are also known to degrade polyethylene, polypropylene, polyethylene glycol, polyurethane, polystyrene, polyethylene succinate, polyvinyl chloride, and polycrcoxy alcohol to different extents.

One study of a mixed microbial culture extracted from cow dung, comprising of thermophilic Pseudomonas sp., Bacillus sp., Paenibacillus sp. and Stenotrophomonas sp., was incubated with HDPE and LDPE plastic polymers for 120 days (Sarayaughan et al., 2017) causing nearly 55% and 77% of their weight and with increased incubation period gave better results. Along with this, many other factors also need to be altered for biodegradation to improve efficiency. Even though some polymers like polyurethane have very high durability, many Pseudonas species like P. aeruginosa, P. floreens, P. protegens, and P. chlororaphis have shown degrading ability (Carr et al., 2020).

Fungal isolates from municipal landfills such as Mucor circinelloides and Aspergillus flavus have been known to degrade LDPE (Kunlere et al., 2019). In another study, six strains of Aspergillus sp. and two strains of Fusarium sp., were reacted in vitro conditions with LDPE polymer. Polyethylene and PP degradation were observed to varying degrees in liquid broth culture, viz., Pseudomonas spp. (37.09% and 28.42%), Streptomyces spp. (46.16% and 35.78%) and Aspergillus spp. (20.96% and 16.84%) in 6 months. The level of degradation was analyzed using CO2 emission test, scanning electron microscopy (SEM), Fourier Transformation Infrared Spectroscopy (FTIR), and colonization studies (Kale et al., 2015). A summary of some of the microorganisms, their source, and biodegradation of plastics have been mentioned in Table 3 (Kale et al., 2015).

According to a few reports two microorganisms namely, Brevibacillus borstelensis and Rhodococcus ruber can use polyethylene as the sole carbon source, since they can break down the carbon backbone of the polymer. A few fungal species like Penicillium simplicissimum YK, Aspergillus flavus and Mucor rouxii NRRL1835 have also been known for quite some time now for their polyethylene degrading ability. Using FTIR technology the polyethylene degradation of 61% by Microbacterium paraoxydans and 50.5% by Pseudomonas aeruginosa was recorded after an incubation period of two months. Whereas, in another study, 47.2% weight loss of the polythene polymer was recorded after incubation of 3 months using the microbe Aspergillus oryzae. Polyethylene discs were added into shaking tubes along with the broth and incubated for 8 months, at pH 4 and room temperature conditions, with the organism Phanerochaete chrysosporium recorded a 50% weight loss in the discs (Kale et al., 2015).

In some studies, it was also noted that the pre-treated polymers could be degraded more easily than the original plastic waste. For example, a study using irradiated and non-irradiated LDPE films were treated with microorganisms like Aspergillus spp. and Lysinibacillus spp. were monitored for their biodegrading capabilities. In the case of irradiated films, there was a 29.5% biodegradation observed and in the case of non-irradiated films, only 15.8% biodegradation was observed (Esmaeili et al., 2013). Further, the decrease in percentage of carbonyl index (CI) of the LDPE polymer was higher in the case of UV-irradiated films, when it was allowed to degrade in the soil as compared to in vitro, with a specifically selected organism. In another study, 8 isolates out of the 25 isolates from landfills were selected and purified for their plastic degrading abilities. Of the eight, one of them even exhibited a 17% biodegradation, after one month of incubation in liquid culture with 130 rpm, kept at 37 °C (Kale et al., 2015).

Sometimes, the microorganism can indirectly facilitate the process of plastic waste clean-up, even if they cannot directly digest the polymers (Urbanek et al., 2018). An interesting study using P. aeruginosa as bio-film was conducted to trap the microplastics and settle them at the bottom of the bioreactor. Once the microplastics are captured by the biofilms, they can be released from the biofilm matrix, with the help of the biofilm dispersal gene (Kaplan, 2010). This gene allows exclusion of microplastics from the matrix. The microplastic collected in this manner can then be recovered and recycled at our convenience (Liu et al., 2021).

8.3. Enzymes involved and their action

Different molecular mechanisms such as chemical, thermal, photo, and bio-degradation can result in plastic polymer degradation. Plastic polymers being hydrophobic, in nature reduces the accessibility to microbial species for breakdown and assimilation. This problem can be overcome by treating plastics with enzymes that add functional groups to the polymer backbone and improve their hydrophilic nature, thereby resulting in the degradation of the main polymer chain via reduction in the molecular weight of the polymer (Aamer et al., 2009). These shorter fragments are water soluble and can easily be absorbed by the microbial cells for metabolism. Aerobic organisms will release CO2 and water as end products while, anaerobic organisms will release CO2, water as well as methane. These gases can be collected and used for various applications. These oligomers and monomers can also be used in many re-polymerization techniques, to produce recycled polymers or they can be converted to organic intermediates like acetones, acids, or ketones (Kale et al., 2015).

Some of the physical parameters such as temperature, pressure, and moisture are involved in the mechanical breakdown of the polymer, which is even essential for the enzymes and microbial metabolites. The extracellular enzymes, typically do not penetrate the polymer, thus making the bio-degradation of plastics, only a surface erosion process. In the process of plastic degradation, the pro-oxidants catalyze the formation of free radicals in polythene. These free radicals react with molecular oxygen and then attack the polythene matrix to break them down into monomers or oligomers. When the enzymatic degradation of plastic polymers happens via hydrolysis it follows two major steps: the enzyme first binds to the polymer and secondly, it catalyzes the bond cleavage using a water molecule (Kale et al., 2015).

Lignin has a very complex polymer structure that can be compared with plastic polymers. Lignin-degrading microorganisms, like white-rot fungi were extensively screened to check for their plastic degrading capabilities. Polyethylene degradation with fungal species IZU-154, Phanerochaete chrysosporium, Trametes versicolor under different nutritional conditions was attempted and it was observed that manganese peroxidase (MnP) is the major enzyme involved in polyethylene degradation (Iiyoshi et al., 1998). This discovery encouraged researchers to use manganese peroxidase (MnP) to treat polyethylene polymers in the presence of tween 80, Mn (II), and Mn (III) chelators. The enzyme laccase (La) is also a well-studied degrader of aromatic substrates, and thus it was used in the oxidation of the hydrocarbon backbone of polyethylene. Using cell-free laccase, 20% reduction in the average molecular weight of the polythene was observed (Kale et al., 2015).

The fungi Chaetomium globosum secretes both, La and MnP enzymes that can be used effectively to treat polyethylene. The mushroom Pleurotus ostreatus is capable of degrading oxo-biodegradable plastics without any pre-treatment of plastic with UV or thermal radiation. After 45 days of incubation, small holes were observed on the surface of the plastic surface due to the formation of hydroxyl groups and carbon-oxygen bonds. The
degradation of the dyes used in the bags was also observed in some cases (Sowmya et al., 2014).

Owing to their simpler structure, aliphatic polyesters can easily be broken down by enzyme activity when compared to aromatic polyesters even at room temperatures. Di Bisceglie et al. (2022) discovered the enzyme cutinases efficient for degradation of aromatic polyesters. A lot of investigations and studies have been done using cutinases and their modifications for the hydrolysis of PET polymers. The bacterium species Ideonella sakaiensis 201-F6, isolated from PET bottle recycling plants, showed the ability to digest various other polyesters at a temperature range of 40–70 °C (Vollmer et al., 2020). The emissions of CO2 from the transport of these waste materials are trying to improve its sustainability. It can be defined as the comparative study/assessment of all the environmental impacts on a particular product, process, or activity at different stages of its lifetime. It is a complete study from cradle to grave, starting from the extraction, transportation, and processing of raw materials; manufacturing; transportation; use, re-use, and maintenance; recycling; material; energy and water consumption; emissions; to the final disposal. It is important to compare the LCA studies, to find the best product, and for that, the assumptions and methodologies used in each step of a product's lifetime must be well documented, clear and consistent. A few environmental impacts that are evaluated for almost all products are toxicity to humans and other living organisms; freshwater and marine ecotoxicity; terrestrial ecotoxicity; acidification (of soil and rains); eutrophication; global warming potential; ozone depletion; depletion of fossil fuels (coal, petroleum, and natural gases); abiotic depletion of mineral resources; visible pollution in terms of litter; photochemical oxidation; renewable and non-renewable energy use (Ojeda, 2013).

Assessment of the CO2 emissions during different stages of the plastic lifecycle yielded that more than half the emissions arise from plastic production, whereas incineration of the final waste gives rise to only one-third of the emissions, and less than 10 wt% of emission is associated with final product assembly like multilayer packaging (Hopewell et al., 2009). The emissions of CO2 from the transport of these waste materials to treatment plants are minimal. Further, the pyrolysis products like liquid

### Table 3

| Sl. no. | Plastic polymer | Microorganisms | Source of isolation | Incubation time (days) | Weight loss (%) |
|--------|-----------------|----------------|--------------------|------------------------|-----------------|
| 1      | Low-Density Polyethylene (LDPE) | *Rhodococcus ruber* C208 | Soil of disposal site | 30 | 4 |
|        |                  | *Bacillus cereus* F20 | Marine water | 180 | 2.5–10 |
|        |                  | *Pseudomonas* sp. AKS2 | Waste dumping soil | 45 | 5 |
|        |                  | *Bacillus subtilis* H1584 | Marine water | 30 | 1.75 |
|        |                  | *Serratia marcescens* | Ground soil | 70 | 36 |
|        |                  | *Aspergillus* sp. | Soil (Plastic waste disposal site) | 7 | Only 4 g/L CO2 evolution |
|        |                  | *Fusarium* sp. F6 | Soil from Municipal solid waste | 28 | 32 |
|        |                  | *Brevibacillus borstelensis* (strain 707) | Soil | 30 | 30% reduction in Mol. Wt. |
| 2      | High-Density Polyethylene (HDPE) | *Pseudomonas* sp. GMB7 | Plastic waste from dumping sites | 30 | 12–15 |
|        |                  | *Arthrobacter* sp. GMB5 | Plastic waste from dumping sites | 30 | 12–15 |
|        |                  | *Achromobacter xylosidans* | Soil | 150 | 9.38 |
| 3      | Polystyrene (PS) | *Xanthomonas* sp. | Field soil | 8 | 40–56 |
|        |                  | *Sphingobacterium* sp. | Field soil | 8 | 40–56 |
|        |                  | *Bacillus* sp. STR-YO | Field soil | 8 | 40–56 |
|        |                  | *Rhodococcus ruber* C208 | Field soil | 8 | 40–56 |
|        |                  | *Rhodococcus ruber* C208 | Soil from the disposal site | 56 | 0.8 |
|        |                  | *Rhituspor australis* NA1 | PS film buried in Soil | 56 | – |
|        |                  | *Aspergillus terreus* NA2 | PS film buried in Soil | 56 | – |
| 4      | Polypropylene (PP) | *Phanerochaete chrysoraphium* | Plastic dumping site | 365 | 4–5 |
|        |                  | *Engydomonium album* | Plastic dumping site | 365 | 4–5 |
|        |                  | *Aneurinibacillus aneurinilyticus*; | Sewage | 140 | 22.8–27 |
|        |                  | *Brevibacillus agr* | Landfills | 140 | 22.8–27 |
|        |                  | *Brevibacillus agr* | Landfills and sewage | 140 | 22.8–27 |
| 5      | Polyvinyl Chloride (PVC) | *Aureobasidium pullulans* | Atmosphere | 42 | 3.7 |
|        |                  | *Bacillus sp.* AIW2 | Marine | 90 | 0.26 |
|        |                  | *Phanerochaete chrysoraphium* | Plastic disposal site | 28 | 32 |
|        |                  | *Pseudomonas coriolilis* | Soil | 45 | 13 |
| 6      | Polyethylene Tetrathalate (PET) | *Ideonella sakaiensis* | Soil near plastic recycling sites | 1 | 1 |
|        |                  | *Saccharomycopsis viridis* | Hot compost | 3 | 27 |
|        |                  | *Humicola insolens* | Manure Compost heaps | 6 | 97 |
|        |                  | *Thermobifida fusca* | Dry fruit compost | 95 | 97 |
|        |                  | *Fusarium solani* | Soil | 6 | 27 |
fuel which replaces conventional fuels and natural gases help in saving almost 30 wt% of emissions (Geyer et al., 2017). The CO2 savings from dissolution/precipitation methods are almost at 65-75 wt%, which is the highest among all other methods, since these methods don’t involve any bond breaking or reforming. Solvolysis involves the efficient conversion into high-value recycled products saving almost the same amount of CO2 as dissolution. Although, for many of the recycling methods, if renewable energy is used for electrification, then the overall recycling process can also become more sustainable. However, this cannot be included during the LCA as this energy source is not directly related to the recycling method and will therefore not be counted. Variation in the life cycle assessment is mainly caused due to the differences in the carbon content of the material and energy requirements of production. Differences may also be observed based on the plastic-type being assessed, because of melting point, tensile strength, viscosity, and energy content that affect the process parameters (Vollmer et al., 2020).

Bearing in mind, the many ways in which plastics affect the environment through different stages of their life cycle, polymer production in the future can be looked at more sustainably. For example, using CO2-derived methanol will further decrease the emissions. (Fig. 8). The LCA of products also clearly indicates that the technologies that cause the least structural breakage/bond breakages produce a higher quality of recycled products and also less harm to the environment (Schwarz et al., 2021). Moreover, by including the cost of CO2 emissions in the final product, polymers produced from fossil sources will become more expensive, encouraging more manufacturers to go for sustainable and recycled plastic polymers (Vollmer et al., 2020).

The life cycle assessment is aimed towards a circular economy than a linear one ensuring minimum wastage. In the case of plastic products, working towards a circular economy would imply constantly trying to produce monomers and oligomers to be re-polymerized after purification. (Fig. 9) The LCA of products also clearly indicates that the technologies that cause the least structural breakage/bond breakages produce a higher quality of recycled products and also less harm to the environment (Schwarz et al., 2021). Moreover, by including the cost of CO2 emissions in the final product, polymers produced from fossil sources will become more expensive, encouraging more manufacturers to go for sustainable and recycled plastic polymers (Vollmer et al., 2020).

10. Circular economy and other alternatives to plastic recycling

The fact that plastic usage has significantly improved our lives is undeniable, but since their disposal and management have become an even bigger issue, we must find more sustainable alternatives to the same (Patricio Silva et al., 2021). For such measures to be adopted into the mainstream, there must be a good collaboration among all the top stakeholders who are ready to invest in more sustainable methods and products. Along with them, the government also must make strict regulations, and standardize product quality. There must be taxes/penalties imposed on CO2 emissions that take into consideration the environmental costs. This will greatly increase the cost of fuel-based plastic usage and encourage more sustainable options. It will also encourage the adoption of newer disposal methods (chemical recycling/bio-degradation) which are less harmful to the environment. Similarly, stricter regulations on the design of packaging materials, will ensure more recycling. Further, we must focus on research and innovation that produces newer products from plastics having higher quality and value (Vollmer et al., 2020). The concept of circular economy is a wholesome approach towards the economy, by taking into consideration its impact on all fields of business, society, and the environment. It is a system that works towards constantly keeping a product in use, until it has been used up to its full potential, and generated the least or no amount of waste. Adopting such a system will have a progressive impact on our economy as well as the planet. These firm steps taken today can reduce the CO2 emissions in the atmosphere by almost 50% in the next 10 years (Bucknall, 2020).

Some of the novel methods being developed in recent times that might help us work towards this goal are discussed below:

10.1. Bioplastics

Bio-based plastics (polymers that are partially or completely derived from biomass), have been emerging as a sustainable (although short-term) alternative to conventional plastics, by replacing fossil fuel with renewable resources (Aragaw and Mekonnen, 2021). These biopolymers are synthesized from biological sources such as plants, microorganisms, animals, etc. Bio-polymers adopt the properties of synthetic polymers showing effective moisture resistance, long shelf-life, and high tensile strength (Bhatia et al., 2021). In addition, bio-based plastics have the potential to decrease carbon footprint and increase recycling targets such as home composting and waste management efficiency. Due to their adjustable degradation rates and sustainable thermophysical properties, aliphatic polymers (e.g., polyactic acid, PLA and polyhydroxyalkanoates, PHA) and furanic-aliphatic polymers (e.g., Polyethylene2,5-furandicarboxylate, PEF and Polyethylene2,5-furandicarboxylate-co-polyactic acid, PEF-co-PLA) are of particular interest as building-blocks for PPE and other single-use plastics (Siracusa and Blanco, 2020).

One of the limiting factors for the industrial application of mass PHA production is the cost of raw materials like pure carbon and nitrogen. Widely available waste organic material can be used as an option for cost-effective PHA production. Waste generated from industries (dairy, food processing, biodiesel, etc.), household, and municipal waste are surplus and available throughout the year to be utilized as feedstock for microbial fermentation and PHA production. The availability of the feedstock in a particular geographical region must also be taken into consideration (Bhatia et al., 2021).

Another important aspect of the PHA synthesis process is selecting the PHA accumulating microbe. Over 300 species of microorganisms have been identified (and several more under investigation) that can accumulate PHA granules in a cell. Some well-explored microbes that can utilize a variety of carbon sources for producing different types of PHA are Ralstonia, Pseudomonas, Halomonas, Burkholderia, Rhodospirillum. The modifications in the metabolic pathway in the PHA synthesis is one of the crucial strategies to produce the desired type of PHA copolymer. There are several aspects of production contributing to the high costs of PHA, like the slow growth of microorganisms, high energy requirements for sterilization and aeration processes, low rates of conversion of raw materials to PHA and expensive downstream processing. Further research in this area should focus on the aforementioned issues about the high cost of PHA and address methods in which the same can be overcome allowing PHA to be synthesized on a much larger scale (Bhatia et al., 2021).

10.2. Design of plastics

To address the problem, we must dive into the root of it which, in this case, lies in the design of the plastic product itself. If the plastics are designed with the intent of recycling, then the recycling of plastic polymers could be done far more easily. We can produce 100% poly-olefinic plastics without using any additives and they can degrade during melting and re-extrusion processes. If such polymers could be designed, they degrade under predetermined conditions into their monomers or oligomers, which would be a key step forward in the recycling of plastics (Vollmer et al., 2020).

10.3. Vitrimerisation

Thermoset plastics have covalent cross-links with permanent networks that are difficult to reshape, reprocess or even recycle. Vitrimer type plastic, an innovative and novel discovery by Leibler and his co-workers (ref), are also cross-linked polymers but they have dynamic covalent networks. These dynamic networks can be rearranged by using higher temperatures or other stimuli, allowing them to be recycled without losing their strength and original properties. In the mechano-chemical process of vitrimerisation, metal-carboxylate ligands are formed. These serve as junctions for the transesterification reaction. This practical design will help provide new
insights into the possibility of eliminating "end-of-life" thermoset polymers (Yue et al., 2020).

11. Knowledge gaps and perspectives

An early and critical lagging in the overall planning for efficient implementation of plastic waste management is the reason for the rise of another bigger environmental crisis during the ongoing pandemic. The statistical data on the extra plastic waste generated from PPE and medical waste, apart from the normal waste that was being produced before the pandemic, is truly very shocking. It is therefore important that we focus our attention on new and innovative methods of plastic production, such that it will help us easily handle the waste thus generated. There is a dire need for people worldwide to move beyond the linear economy and work towards a circular economy. The pandemic has pushed us to be more alert and prepared for such a situation, if and when it arises in the future. The scientific community, corporate society, and government institutions, all over the world must come together to help in the development of more sustainable methods and encourage them by providing the necessary economic and social support.

The COVID-19 pandemic has given us the necessary push that was needed to start taking the plastic management issue more seriously. Keeping in mind the different methods of repurposing and recycling plastics discussed earlier in this paper some recommendations to work towards a sustainable environment and circular economy are as follows:

- As the number of cases is rising rapidly, there is a dearth of PPE kits for front-line workers. To meet these demands, it is necessary to encourage, the new innovations and research working towards the production of eco-friendly and reusable PPE kits. This method makes plastic polymers almost immortal, thus encouraging continuous reuse of the polymers for different purposes.
- The usage of cloth masks must be encouraged among the general public, rather than single-use commercially available plastic masks. Since the general public is less prone to exposure to the virus compared to health care workers who are close to affected patients, the usage of cloth masks provides a good amount of protection.
- When it comes to plastic polymers in medical kits, it is rather difficult to replace them with these types of equipment. To reduce wastage in this area we can consider the thorough sterilization and reuse of materials such as pipetting tips and testing plates wherever feasible. The usage of eco-friendly swabs can also be considered in place of plastic swabs.
- Microbial degradation is one of the most recent and promising fields of research to degrade plastic polymers. These microbes have the unique ability to degrade and utilize carbon, hydrogen, nitrogen, etc. from plastic polymers for their growth. They release enzymes that are produced either as extra or intracellular enzymes that can degrade the polymers. The only disadvantage in most microbial degradations, however, is the time factor. Deep analysis and research in this field will surely help us in developing environments that increase degradation in a shorter amount of time.
- A combination of different sterilization and repurposing methods that have been discussed earlier in this paper must be studied well and developed in such a way that it allows maximum usage of the polymer and results in a minimum amount of wastage. The use of automation and robotics integrated with artificial intelligence (AI), machine learning (ML), and the internet of things (IoT) will play an important role in plastic waste segregation and recycling, especially during this pandemic.
- The government, corporate sectors, and scientific communities must all come together to develop and strictly implement laws regarding the proper disposal and treatment of plastic wastes. Further, setting up mobile treatment facilities temporarily at locations will help treat and get rid of the waste on-site.
- Educating the general public at the school and university level, as well as at training centres, will ensure that the problem is tackled from the grassroots level. This can be done by public educative campaigns that work towards creating awareness and spreading more knowledge about the harmful effects of plastic waste mismanagement on the environment.
12. Conclusions

Plastic usage in several forms during COVID-19 has continued to be imperative despite its harmful effects. The generation of plastic wastes in times of a pandemic, especially from test kits and PPEs for the frontline workers, is inevitable. We cannot completely ban the usage of plastic-based PPE or medical kits. Instead, we must find an eco-friendly alternative for them to lessen damage to the environment and landscape as against the current scenario. There must be an implementation of a few short-term and long-term activities that would decrease the deleterious effects of plastic residues released from PPE and COVID-19 test kits. Based on the discussion presented in the review, it is possible to get rid of these wastes using the methods highlighted. The majority of the methods discussed have their shortcomings in terms of cost, infrastructure requirement, or incubation time required to complete the process. To work towards a circular economy, a multifaceted/interdisciplinary approach is necessary to deal with the complexity of the problem. Among all the above methods, the microbial degradation approach (to degrade the polymers and to produce bio-based polymers from biowaste) seems to be advantageous. Considering the number of different microorganisms and their specificity to the polymers, it would be apt to frame an ideal combination of microbes to deal with medical plastic problems. This method has a lot of scope for research on the degradation of plastic wastes. The collection and sorting infrastructure will also need to be improved, by implementing stricter regulation. Government policies must be put into place to make sure that such methods get maximum funding. This will help increase the demand for the same and in the long run slowly work towards reducing the cost of eco-friendly recycling and repurposing methods. Successful adoption of newer recycling methods will require the cooperation of researchers, the industrial community, and the government. Many new practices are already finding their way into real-world applications. Spreading knowledge and educating the youth about the same will only help newer innovations come into the markets.

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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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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