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The global market of PET production: from origins to recycling

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ABSTRACT

Plastic handling and manufacturing have recently increased dramatically owing to technological advancements and rising living standards. Consequently, the amount of plastic waste has significantly escalated, seriously pressuring the whole ecosystem. The impacts of waste accumulation in the environment frequently have detrimental effects on living organisms. Sustainable development goals (SDGs) propose balanced and feasible development of entire humanity, protecting natural resources and bringing a clean environment. Poly (ethylene terephthalate) - PET is a common plastic that can seriously threaten the environment if it is not handled appropriately. This review paper tends to show recent trends in the production and recycling of PET polymer on a global scale. The basis of PET chemistry together with possible applications was presented. A target period, from 2020-2024, was used to examine the quantity and main industrial suppliers around the world. Therefore, some sources state that in 2024, nearly 28 Mt of PET was produced and China was the main producer with a global share of 31%. Adequate management of the mentioned polymer is necessary for building an eco-friendly climate for future generations.

Keywords: poly(ethylene terephthalate); sustainable development; environmental protection; waste management; biological decomposition

1. Introduction

The increase in the number of inhabitants on planet Earth has caused the demand for greater industrial production. The constant requirement for technological development and growth of the market has led researchers and innovators to thoughtfully study, synthesize, and apply various metallic and non-metallic materials with industrial applications. In this regard, in the 20th century, the development and utilization of several types of different polymer materials began, which found its application in many industrial branches, such as construction (Zulkernain et al. 2021), packaging (Schyns and Shaver 2021), and transportation (Chauhan, Kärki, and Varis 2022). Given that polymers are affordable, lightweight, and long-lasting, they became the main constituents of various plastic materials. A non-renewable resource called fossil hydrocarbons is the source of synthetic plastics, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polycarbonate (PC), polyvinyl chloride (PVC), and poly(ethylene) terephthalate (PET) (Soong, Sobkowicz, and Xie 2022). PET polymer has attracted particular attention, due to its extraordinary physicochemical characteristics, i.e. outstanding chemical resistance, acceptable thermal stability, and ease of storage. These are some arguments for PET to become one of the most extensively used plastics worldwide.

The aforementioned reasons make plastic products unavoidable in every area of citizens' lives. Globally, the plastic market has increased from 2023 to 2024 by $80 billion. It is predicted that, until 2030, the value of the market will be raised at a compound annual growth rate (CAGR) of 7.6%. Regions with the most enlarged production and usage are Asia-Pacific, North America, Europe, and Africa (Research and Markets 2024).

Developed consumer awareness, in addition to its positive effects on industry and the whole economy, also presents certain disadvantage. The first problem is the generation of a large amount of waste that needs to be disposed of. In 2022, the European Union countries recycled 41% of all generated plastic packaging waste, indicating a slight increase compared with 2012 when the rate stood at 38%. Slovakia recorded the highest recycling rate at 60%, while in contrast, the lowest rates were recorded in Malta, where only 16% of the produced plastic packaging waste was recycled (Eurostat 2022). In 2019, the price of virgin PET flakes was approximately USD 900/t, while the price of recycled PET was around USD 1000/t (Seval 2021). This made one of the biggest problems for the complete society since the desire to grow the share of PET recycling was impeded. Although plastics are significant resources in many ways, widespread usage of plastic items over the past few decades has had a detrimental impact on the environment because of low recycling rates following the production of single-use plastics. The volume of plastic produced is predicted to rise steadily over the next several decades despite evident drawbacks (Hopewell, Dvorak, and

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Kosior 2009). Concern over induced pollution in the environment has grown as a result of the rising demand for plastic items and the scarcity of practical and affordable methods for recycling spent plastics together with the depletion of natural resources (Soong, Sobkowicz, and Xie 2022; Gabisa, Ratanatamskul, and Gheewala 2023).

Both aquatic and terrestrial ecosystems have been significantly impacted by the microplastics (particle size < 5 mm) created by these plastic wastes (Gabisa, Ratanatamskul, and Gheewala 2023). Therefore, analyzing PET plastic's creation, utilization, and potential reuse is essential to reducing its negative effects on the environment. PET polymers are thought to take hundreds of years for environmental microbes to fully break them down (Soong, Sobkowicz, and Xie 2022). Waste PET buildup is now steadily rising and beginning to endanger ecosystems worldwide (Soong, Sobkowicz, and Xie 2022). According to estimates, the plastics industry contributed 4.5% of world greenhouse gas emissions in 2015 (Cabernard et al. 2022).

This work aims to present the newest data on the production and recycling of the PET polymer. Together with this data, the basic chemistry of PET polymer with its physicochemcal characteristics will be presented. Further, the potential applications together with some novel recycling technologies will be shown. This paper tends to help researchers better understand the impact of PET recycling both economically and environmentally.

Hence, the following are some of the primary goals of this study:

1. Providing better insights into PET polymer with special attention to physicochemical properties and its production,
2. Presenting the worldwide market and distribution of PET with an economic overview and possible impacts on society generally,
3. Exploring possible routes for recycling waste PET and impacts on the environment.

2. Insights into PET

The industrial history of PET polymer starts at the beginning of the 20th century. In quest of novel synthetic fibers, DuPont chemists created PET for the first time in North America in the middle of the 1940s (Xin et al. 2021). The polyester family includes poly(ethylene) terephthalate (PET), a thermoplastic polymer that softens when heated and hardens again when cooled. Figure 1 displays the PET monomer formula. PET is extensively used to make different types of engineering plastics (usually in conjunction with glass fibers), synthetic cloth, and packaging for food and beverages. The CAS number of PET is 25038-59-9.

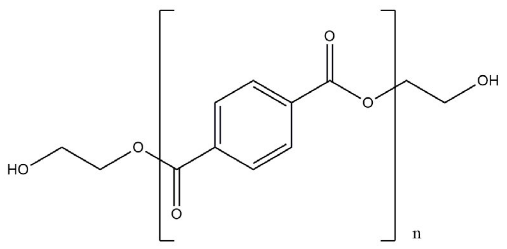

Fig. 1. PET structural formula

A polycondensation between a di- or polyfunctional carboxylic acid and a diol polyfunctional alcohol is the most common method of polyester synthesis (De Vos et al. 2021; Ravindranath and Mashelkar 1986; Botelho et al. 2001). A variety of polyesters with adjustable characteristics may be created, depending on the basic elements used for their synthesis (De Vos et al. 2021).

2.1. Chemistry of PET

There are some chemical routes for the synthesis of PET polymer. Terephthalic acid (TPA) or dimethyl terephthalate (DMT) and a diol (ethylene glycol - EG) undergo polycondensation to create PET on an industrial scale (De Vos et al. 2021). Currently, fossil fuels are the primary source of these monomers used in commercial PET synthesis. Para-xylene is the starting point for the production of both TPA and DMT (Tomás et al. 2024; Fadzil, Rahim, and Maniam 2014). The oxidation of ethylene to produce ethylene oxide, which is then hydrolyzed with water, is the first step in the commonly used commercial synthesis of EG (Carney and Stice 2017).

The first synthesis technique for obtaining PET was melted polycondensation, which is currently employed in both industrial and research settings (Giol et al. 2018). Two metal-catalyzed processes are involved in this step-growth polymerization, as shown in Figure 2 (Devroede et al. 2009; Ravindranath and Mashelkar 1986). The first reaction step includes esterification or transesterification for the creation of an intermediate pre-polymer. In the former, TPA and the proper diol react, whilst in the latter, DMT is utilized. Under inert conditions, which are created by a nitrogen or argon flow in a system, this phase is typically carried out at 190–230°C (Lefèbvre et al. 1999; Ng and Leverne Williams 1981).

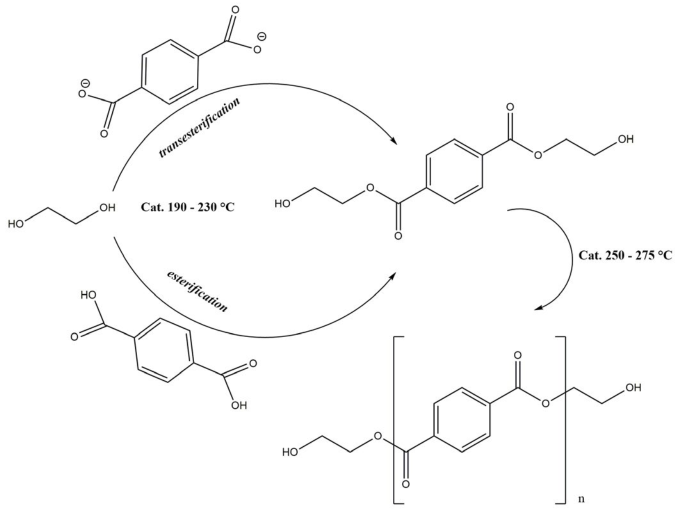

Fig. 2. Step-growth polymerization reaction method used to create PET (De Vos et al. 2021)

The elimination of the by-product is also required in order to move the equilibrium in favor of the pre-polymer site since this reaction is equilibrium. The intermediates are polycondensed to create the final product in the second stage. As a result, the temperature rises to 250–275 °C and the pressure decreases. When a specific melt viscosity is attained, the polycondensation stops (Ravindranath and Mashelkar 1986). At moderate temperatures, catalysts based on zinc, titanium, antimony, and tin are commonly used to increases the rate of reactions (Botelho et al. 2001). The foremost reason for industrial production of PET *via* melt polymerization is because it provides several benefits, such as the ability for production on a large scale using a continuous polymerization process that eliminates the need for further purification (MacDonald 2002).

2.2. Physicochemical characteristics of PET

PET has outstanding qualities that make this polymer tremendously used in various economic areas. Some of them are superior tensile (40 – 60 MPa) and impact strength (4.6 kJ/m²), great thermal stability (-70 – 150 °C), flexural strength (19 – 46 MPa), Young's modulus (55 – 100 MPa), etc. (Olam 2023).

PET is strong thermoplastic polymer, stretchy during processing, mechanically resistant to impact, and with semi-stiffness (Nisticò 2020). The melting points of commercial PET and PET with high levels of crystallinity are 255ºC-265°C and 260ºC-265°C, respectively (Malik et al. 2016). Therefore, PET is not degradable by biota in typical environment (Zhang et al. 2020). For a long time, it was thought that PET is not biodegradable, but with adjustment of conditions, biodegradation processes can be initiated.

PET polymer has no color and can be either translucent (semi-crystalline) or transparent (amorphous). Whether the final structure being semi-crystalline or amorphous depends on the thermal conditions during PET production. It also exhibits gas-barrier qualities against CO_2 and moisture, which is important for food and beverage protection (Demirel 2017). In contrast to other plastics, e.g. PVC, PET is highly inert and does not require plasticizers. The surface of PET can be modified (physical and chemical treatments) or combined with other polymers (such as PC, PP, and PP copolymers) to enhance certain qualities (Nisticò 2020).

The fact that PET has a larger density than water (> 1.3 g/cm^3) suggests that this polymer cannot sink in water, simultaneously with hygroscopic nature itself. This polymer is invulnerable to the most of strong acids and bases, hydrocarbons, and also chemically inert to many solvents and reactants.

2.3. Global production and industrial applications of PET

Thanks to several physicochemical properties, labeled in the previous chapter, that substantially distinguish PET as outstanding for the production of plastic materials, the worldwide market for this polymer is in constant expansion. This rapidly expanding tendency is a severe problem that jeopardizes Goal 12 and Goal 14 of the UN Sustainable Development Agenda (Gong and Xie, 2020). Several marketing agencies and researchers made predictions on market fluctuation in the proposed period.

The global market volume of PET amounted to 25.47 Mt in 2022. By 2030, the PET market volume is expected to reach 35.13 Mt (Figure 3), growing at a compound annual growth rate (CAGR) of 4.1% during the forecast period (Statista 2024). For 2025, it is estimated production of PET will be 28.73 Mt.

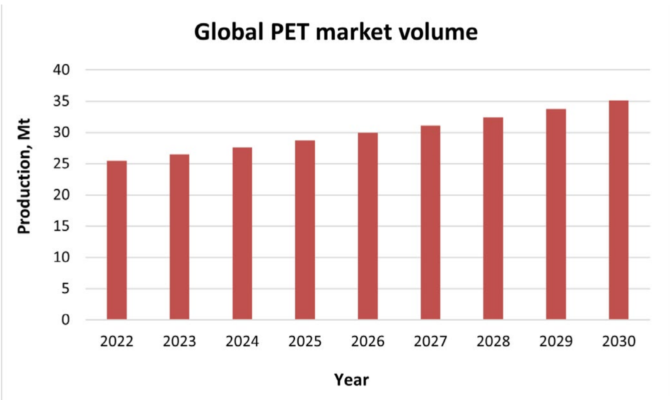

Fig. 3. Increasing of PET production, 2022-2030 (Statista 2024)

According to the report published by Facts and Factors (Facts and Factors 2023), the global PET market size was worth around USD 37.25 billion in 2021 and is predicted to grow to around USD 41 billion by 2030 with a CAGR of roughly 10% between 2022 and 2030. The market is projected to grow at a significant rate due to the growing applications in the packaging industry. The available report analyses the global PET market drivers, restraints/challenges, and the effect they have on the demands during the projection period. By observing the distribution of PET manufacturing by region, it can be seen that China is the main producer with a global share of nearly 31%, followed by the rest of Asia, North America, and Europe (Figure 4).

Among the leading companies in the market for PET are: Far Eastern New Century Corporation (China), Indorama Ventures Public Company Limited (Thailand), SABIC (Saudi Arabia), Reliance Industries Limited (India), Lotte Chemical Corporation (South Korea), Alpek S.A.B. de C.V (Mexico), Jiangsu Sanfangxiang Group (China) (Verified Market Research 2024).

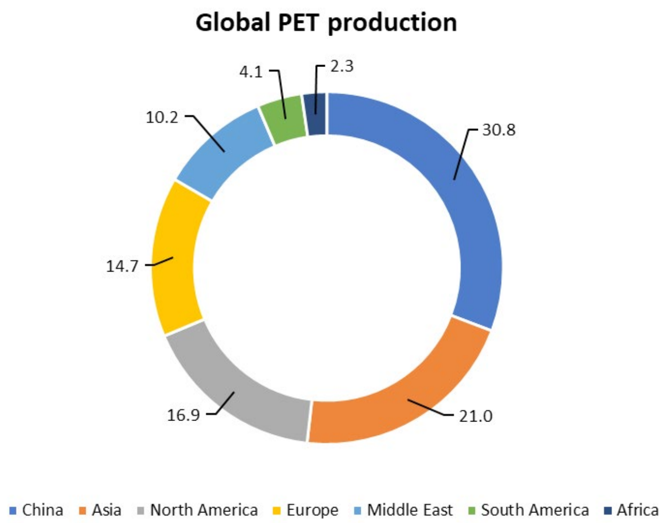

Fig. 4. PET manufacturing worldwide, 2017-2018 (Adroit Market Research 2022)

Bottle manufacturing accounted for up to 30% of all PET output in 2016 (Nisticò 2020). Because the polymer is robust, lightweight, clear, shatterproof, and widely accessible, PET bottles are preferred. Because of this, the bottles are affordable and portable. PET is also helpful in aerospace applications, however, larger molar masses of 120,000 g/mol of polymer are needed since it must endure harsh conditions (Gantillon, Spitz, and McKenna 2004).

Moreover, PET is used in the clothing industry in the production of clothing fiber. PET is also used to produce containers for food and fruit packaging. In textile applications, it is commonly referred to as polyester whereas PET is the generally accepted term in the packaging industry. In the automotive industry, PET found a place in some manufacturing parts (carpets, sound insulation, boot linings, seat covers) (Volpe et al. 2022). The construction industry uses PET for water and sound insulation by the production of different types of geotextiles. Moreover, PET derivates found applications as corrosion inbitors (Khowdiary et al. 2020), supercapacitors (Kim et al. 2015), coatings (Ghosal and Nayak, 2022), photocatalysts (Ribeiro et al. 2020), etc.

2.4. Recycling of PET

PET is manufactured in large quantities on an industrial scale due to a wide range of utilization in commercial applications, from food packaging to automobiles. As a result, PET is prevalent in plastic waste and contributes significantly to pollution (Fayshal 2024; Kibria et al. 2023). Recycling is becoming more popular as a means of preventing waste accumulation in the environment and establishing conditions for the circular economy (Novakovic et al. 2023). Over 70% of PET bottles in Europe were recycled in 2017. Different processes can be employed for treatment of waste PET: physical, chemical and thermal. Recycling of PET has already been discussed in many lengthy evaluations in previous years (Benyathiar et al. 2022; Lamba et al. 2022; Soong, Sobkowicz, and Xie 2022).

The leading solution for an enlarged amount of generated waste PET could be proper waste management. The waste management hierarchy is composed of three main steps: reduce, reuse, and recycle. The process of recycling entails gathering, separating, processing, creating, and providing a new use value for waste materials. Different possibilities for converting waste into value-added products can be applied. The benefits of waste processing are reflected not only environmentally but also economically and energetically. Recycling can help in further areas: avoiding pollution in the environment, raising environmental consciousness, conserving natural resources, lessening the quantity of landfill waste, and easing the waste disposal issue. Products made from recycled elements sometimes need less energy to create than those made from raw materials.

Fundamental possibilities for recycling waste materials involve the implementation of various chemical, physical, and thermal processes. PET may be recycled in four different ways: in primary, secondary, tertiary, and quaternary stages (Babaei, Jalilian, and Shahbaz 2024). Reusing uncontaminated waste from the manufacturing process is known as primary recycling. This is the most convenient waste processing step since the costs of recycling are trivial compared to other listed levels. PET processing facilities are where primary recycling occurs. Primary recycling includes waste collection, separation by waste categories, and washing, before further processing.

Plastic bottles cannot be recycled several times, since the chains of polymers are shortening after each time of processing. Therefore, primary recycling is not the most convenient way to treat waste plastics. Chemically processing combined with physical processes of contaminated plastic waste is known as secondary recycling. Cleaning the material of contaminants by mechanical and chemical treatment is the first stage in this process. Notwithstanding the decline in recyclability, this procedure is crucial to reducing the demand for virgin resources and assisting in the removal of fewer recyclable items from landfills, especially plastic.

Waste polymer materials are chemically converted into monomers as part of tertiary recycling (Chanda 2021). Tertiary processing includes the formation of new materials or chemicals. Through the entire or partial breakdown of lengthy PET polymer chains into oligomers or monomers, this recycling method seeks to extract monomer units. The chemical depolymerization procedure is then started by introducing the obtained PET pellets from the previous steps into a reaction vessel (Xin et al. 2021). Therefore, methanolysis, hydrolysis, glycolysis, alcoholysis, and aminolysis are the five basic processes that underpin chemical recycling (Paszun and Spychaj 1997). The glycolysis of PET plastic to produce virgin PET plastic and diols and dimethyl terephthalate is probably the most applied in industry (Conroy and Zhang 2024; Al-Sabagh et al. 2016; Enache, Grecu, and Samoila 2024).

Quaternary recycling is the process of flaming waste to produce energy. Compared to transferring waste to landfills, energy recovery is the preferable resource-efficient option. The process of turning waste into usable heat, power, or fuel using a range of techniques, including gasification, pyrolysis, and incineration/combustion, is known as energy recovery from waste (Arena 2012). The most often used thermal treatment is incineration, which aims to completely oxidize all of the appropriate element species present in the feedstock material (Lombardi, Carnevale, and Corti 2015).

Municipal solid waste (MSW) can be treated *via* incineration, which also reduces the quantity of solid waste that has to be landfilled while using the material's energy content. However, the rising amount of plastic in MSW is causing operating issues for older incinerators. This is because plastics have a high-yielding calorific value (typically greater than 40 MJ/kg) because of their high hydrogen and carbon content (Zevenhoven et al. 1997). The release of hazardous materials, such as fly and bottom ash containing toxic residues (like lead and cadmium), the leakage of toxic chemical compounds (like dioxins, polychlorinated biphenyls, and furans), and the emission of greenhouse gases (like carbon dioxide, methane, and nitrous oxide) are all concerns associated with the incineration of plastics (Zevenhoven et al. 1997; Okan, Aydin, and Barsbay 2019; Gilpin, Wagel, and Solch 2003).

Although current cleanup techniques have made an effort to lessen the negative effects of PET pollution, they cannot keep up with the growing amounts of PET waste that are released into the environment.

In Serbia, collecting and treatment of waste are constantly growing. Public utility companies, also known as PUCs from local governments, provide the Serbian Environmental Protection Agency (SEPA) with data on municipal waste. Reports were provided by 95 PUCs in 2023 and 104 PUCs in 2022 (SEPA 2023; 2024) and presented in Table 1.

Table 1. Indicators related to municipal waste (SEPA 2023; 2024)

Indicator	2023*	2022**
Total amount of municipal waste generated (million t)	3.07	3.18
Recycled fractions of municipal waste (million t)	0.484	0.561
Exported municipal waste fractions (million t)	0.115	-
Amount of collected and deposited waste (million t)	2.59	2.59
Average waste collection coverage (%)	88.3	87
Average daily amount of municipal waste per capita (kg)	1.26	1.28
Municipal waste recycling rate %	15.5	17.7

* Estimated based on population number in 2022
** Estimated based on population number in 2021

This is demonstrated by the fact that the average daily waste production has increased while the overall amount of municipal waste created has decreased. In comparison to the prior era, the extent of municipal waste pickup is marginally expanding. The municipal waste recycling rate is 15.5%, which is negligibly less than it was the year before.

2.5. *Biological PET recycling*

More recent research has shown that some microorganisms have evolved to create a range of hydrolytic enzymes that enable them to break down and process polymers, even though synthetic polymers were originally thought to be resistant to microbial destruction. Although PET is typically thought of as non-biodegradable, prior research has shown that hydrolytic enzymes may depolymerize it or its copolymers *in vitro* (Barth et al. 2015) or in microbial environments (Nowak et al. 2011; Chandramouli Swamy et al. 2024).

Biodegradation, which is thought to happen after or concurrently with abiotic degradation, is the breakdown or degradation of organic materials by the actions of living entities, such as microorganisms (*i.e.*, bacteria, fungus, and marine microalgae) or enzymes (Khoo et al. 2021; Chia et al. 2020).

There are pleanty of biotic and abiotic elements that substantially cause the PET plastic matrix's macrostructure to break up into tiny fragments (Figure 5). Following their attachment to the polymers, microorganisms that can use plastics as a source of carbon and energy colonize the surface and create biofilms (Jaiswal, Sharma, and Shukla 2020; Shah et al. 2008). The growth of biofilm communities on the polymers' exterior and interior causes biodeterioration, which widens the pores and promotes cracking. The process by which extracellular polymer-degrading enzymes (such as oxygenases, ureases, esterases, lipases, proteases, depolymerases, cutinases, etc.) are released by microbial colonies cause biofragmentation. By completely or partially depolymerizing polymers into oligomers, dimers, and eventually monomers that the body may absorb, these enzymes allow polymers to have their molecular weight reduced and their carbon-chain backbone shortened. Mineralization is the final stage of polymer biodegradation, including the excretion of finished oxidized metabolites such as CO_2, CH_4, N_2, and H_2O.

Conclusion

Depletion of natural resources urges for better exploitation of waste materials. Recycling plays an essential role in significantly contributing to pollution reduction.

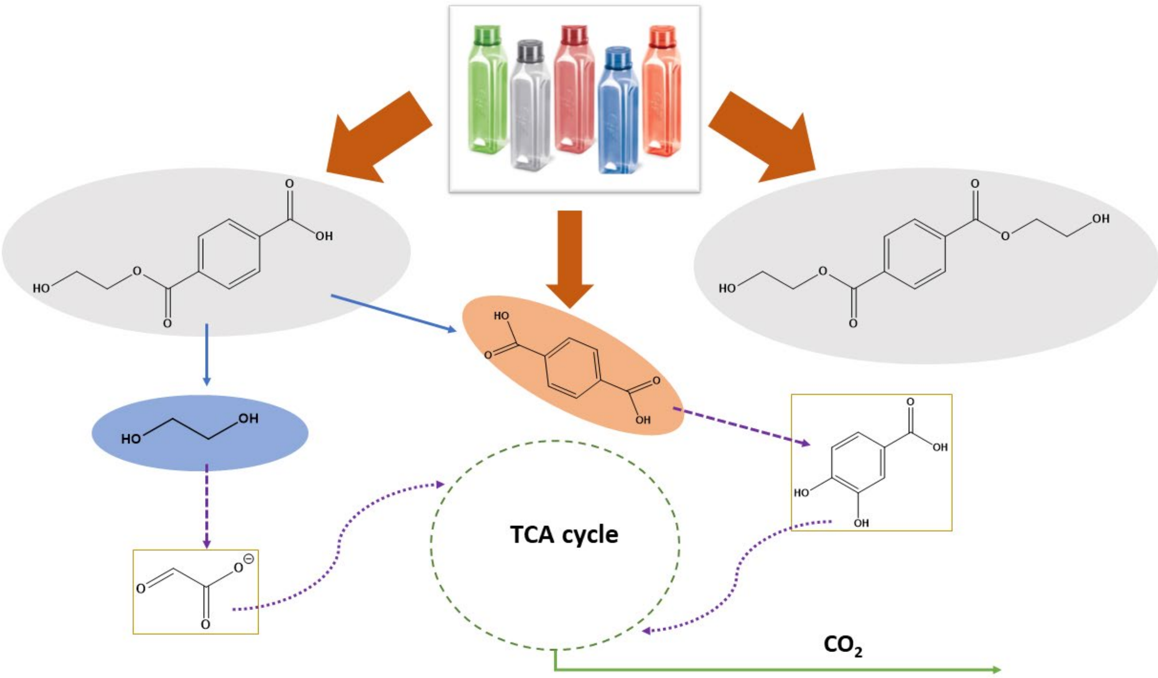

Fig. 5. Biodegradation of PET (Soong, Sobkowicz, and Xie 2022).

This paper critically examines all facets of PET's industrial production, intrinsic physicochemical characteristics, chemical and mechanical recycling procedures. Overlapping sustainable goals with appropriate waste management is crucial for modern society and future generations.

A high content of poly(ethylene terephthalate) is detected in the environment posing negative effects on all living beings. The sector of producing polymers has been growing since widespread use in commercial and industrial applications. As can be noted in this review, the global market volume of PET amounted to 25.47 Mt in 2022, while expected production in 2030 will reach 35.13 Mt. Therefore, the necessity of waste quantity reduction and recycling are main task for numerous researchers and innovators. The recycling is the primar process for conversion of PET into fuels or novel materials with added value. Naimly, conventional techniques which are used in PET degradration are combustion, chemical depolymerisation, schredding etc. Further consideration for better exploitation of waste following the principles of sustainable development could be: developing "greener" technologies for waste treatment, better utilization and invention of new applications of waste materials, and raising citizens' awareness of the importance of reuse and recycling. The usage of microorganisms for PET degradation gained more attention to involve more ecofriendly technologies.

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