17 Microplastics and Synthetic Polymers in Agricultural Soils: Biodegradation, Analytical Methods and Their Impact on Environment

M. Mizanur Rahman, Zahurul Haque, Nazmul Huda, Md. Amdadul Huq, Mamoona Rauf, Md. Maharub Hossain Fahim, and Muhammad Arif

Abstract

Microplastics (MPs) and synthetic polymers (SPs) are emerging pollutants/contaminants worldwide. Due to the significance of soil environment and the demand from scientific communities for increased soil research, it is expected that related studies will rise steeply in the years to come. This present analysis aims to provide an overview of existing information about contamination in soil ecosystems by MPs and SPs. We precisely summarize the types, source, functional analytical methods, exposure routes, contamination of MPs in soils. We also carefully explain the influence of MPs on soil physicochemical properties, plants, and soil biota and determine what we are capable of learning from available data. The chapter critically assesses the efficient MP biodegradation strategies, showing the role of microorganisms and enzymes in the processes with influencing factors of biodegradation. The chapter also outlines the problems of MPs pollution, which would be an emphasis on source management and cleanup.

Keywords

Agricultural soil · Biodegradation · Contamination · Environmental pollution · Microplastics (MPs) · Plastic biodegradability · Synthetic polymers (SPs)

17.1 Introduction

Microplastics (MPs) and synthetic polymers (SPs) are soundless hazards which are measured as a substantial problem in varied environments (Sarker et al. 2020). MPs are heterogeneously diverse plastics (>5 mm in diameter) comprising of plastic granules, fibers, and fragments, which are evolving contaminants (Guo et al. 2020; Cózar et al. 2014). Plastic manufacture has enlarged from 1.5 to 335 million tons in 2016 worldwide (Sarker et al. 2020; PlasticsEurope 2018). The present stages of plastic production, disposal/usage pattern, demographic data, and small recovery rate are the foundations of rising accumulation of plastic waste (Guo et al. 2020).

M. Mizanur Rahman (✉) · Z. Haque · N. Huda · Md.M. H. Fahim
Department of Biotechnology and Genetic Engineering, Faculty of Biological Science, Islamic University, Kushtia 7003, Bangladesh

Md.A. Huq
Department of Food and Nutrition, College of Biotechnology and Natural Resource, Chung-Ang University, Gyeonggi-do, Anseong-si 17546, Republic of Korea

M. Rauf
Department of Botany, Abdul Wali Khan University, Mardan, Pakistan

M. Arif
Department of Biotechnology, Abdul Wali Khan University, Mardan, Pakistan

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Although less than 5% plastics are recyclable materials and domesticated, nonetheless large amounts (4.8–12.7 million tons) of plastic waste are coming into the ocean (Sutherland et al. 2010; Guo et al. 2020; Jambeck et al. 2015). Subsequently, productions of carbon dioxide have increased due to plastics production worldwide (PlasticsEurope 2018).

In recent years, plastics have have been regarded as the severely dangerous pollutants in the environment (Zhang et al. 2015; Sarker et al. 2020). Soil is observed to be the main transportation route for MPs (Zhang et al. 2015; Horton et al. 2017). Disposition of MPs has not been studied in the soil as an important research area with biotic toxicological assay (Hurley and Nizzetto 2018; Zhang et al. 2015). In mulching purposes, polypropylene (PP) and low-density polyethylene (LDPE) are applied as main sources of MPs in agricultural soil (Sarker et al. 2020; Blasing and Amelung 2018). Additional sources comprise composting with littering, sewage, suburban runoff, and sludge wastewater irrigation (Corradini et al. 2019). Their toxic effects have been recognized in marine animals due to occurrence of numerous plastic debris in oceans and coastal watercourses (Hossain et al. 2020, 2019).

Recently, it was demonstrated that the toxicity of MPs transfer from agriculture field to the food chain and thus to humans. Consequently, MPs could be treated as the upcoming hazards to sustainable agricultural and food safety. This chapter focuses on overview of existing information about contamination in soil ecosystems by MPs and SPs with the types, source, exposure routes, contamination level and fate of the MPs in soils.

17.2 Biodegradation and Plastic Biodegradability

17.2.1 Biodegradation

Biodegradation is a biological process which involves the degradation and assimilation of polymers into their simpler and nontoxic forms such as carbon dioxide (CO_2), methane, water, and biomass using living microorganisms (Kumar and Maiti 2016; Raaman et al. 2012). Polymers are converted biochemically by reducing their molecular mass, mechanical strength and the external properties (John and Salim 2020). *Pseudomonas flourescens*, *Pseudomonas aeroginosa*, and *Penicillium simplicissimum* are the most common biodegrading strains (Ahmed et al. 2018; Raziyafathima et al. 2016).

Biological degradation of high molecular weight polymers is primarily regulated by two steps that may occur in soil, water, or human beings (Eskander and Saleh 2017; Tokiwa et al. 2009). The first step is known as fermentation/fragmentation, where macromolecular chain with high molecular weight is converted into oligomers (Fig. 17.1). The second step is known as a mineralization in which oligomers and monomers are mineralized into water, carbon dioxide (CO_2), methane, and biomass by using microorganisms (Agarwal 2020). Biodegradation is affected by many environmental factors, including the accessibility of light, pH, oxygen, temperature, moisture, microorganisms, and type of enzyme and concentration of enzyme. Under different conditions, the identical polymer display diverse rates of degradation (Agarwal 2020).

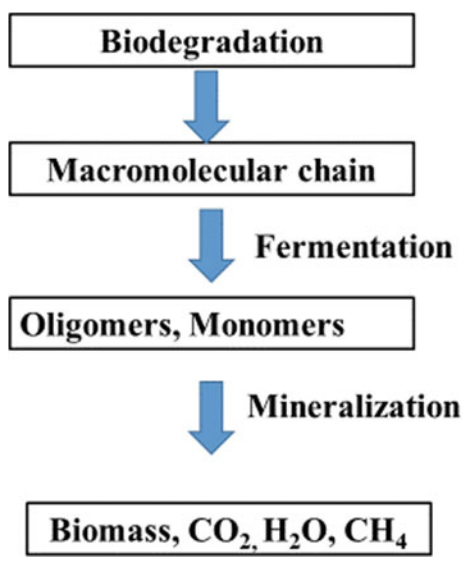

Fig. 17.1 Process of biodegradation

17.2.2 Plastic Biodegradability

The word ``biodegradation' applies to materials which are either decomposed or mineralized into ultimate products of carbon dioxide and water when exposed to a particular microbial environment. Polymers that are degraded in this way are referred as biodegradable polymers which, instead of raw materials, are very much dependent on the chemical composition of polymers (Kijchavengkul and Auras 2008). Plastics are degraded by various mechanisms such as chemical, photo, thermal, and biological degradation. Plastic degradation is a physical or chemical alteration in polymers caused by environmental causes, for example, heat, light, humidity, and biological and chemical activity (Tokiwa et al. 2009).

Bioplastics (BPs) are made of bio-based and biodegradable plastics. However, in our view, BPs consist of biodegradable (such as fossil-based plastics) or bio-based plastics (biomass produced plastics or renewable sources) (Tokiwa et al. 2009). BPs are classified as ``plastics' where the carbon (100%) is extracted from renewable sources, for example maize starch and soybean cellulose and protein in agricultural and forestry sectors (Alshehrei 2017).

The biodegradability of plastics can be defined as a preliminary point for biological processes or as the interruption of plastic polymers or monomers (Annemette 2019). Without leaving detectable toxic traces, biodegradable BPs are completely degraded by microorganisms (Jain et al. 2010). The utmost popular forms of biodegradable polyester plastics include polylactic or polylactate acid (PLA), poly propiolactone (PPL), poly 3-hydroxybutyrate (PHB), polycaprolactone (PCL), poly 4-hydroxybutyrate (P4HB), polyethylene succinate (PES), poly ester carbonate (PEC) (PHBV), poly butylene succinate (PBS), and poly 3-hydroxybutyrate-co-3-hydroxyvalerate plastics (Northcott and Pantos 2018).

17.3 MPs and SPs

MPs obtained from non-biodegradable polymers can create a potential threat to health and the environment (Annemette 2019). MPs particle size in ranging from 100 nm to 5 mm (ng et). The incorporation of MPs into the environment can be thriven by laundering cosmetic beads and textile, fabrics or indirectly by breaking up of bigger plastic parts (mechanical degradation). Because of their small size, many species at almost all food chains, especially in marine ecosystems, including zooplankton, coral, fish, birds, and marine mammals, consume microplastics easily. It was noted that seabirds (99%) had swallowed MPs, and by 2050, more than 600 aquatic animals (nearly 15%) which are predicted to be affected by MPs ingestion or predicament in MPs marine litter (UNEP 2016). In addition to causing direct landscape issues, the pervasive presence of plastic waste and MPs poses possible environmental threats to living species, including humans (Shen et al. 2019; Diepens and Koelmans 2018; Miranda and Carvalho-Souza 2016; Fossi et al. 2012).

SPs are described as polymers that are manufactured artificially. They are also recognized as man-made polymers. Polyethylene (PE), polyamides (nylon), polystyrene (PS), poly vinyl chloride (PVC), teflon, epoxy, synthetic rubber, and some others are several examples of SPs (Verma 2004). In a regulated environment, SPs are mainly derived from petroleum oil and consist of carbon–carbon bonding. Using synthetic polymers, millions of daily applications are made. The groups of thermoplastics, thermosets, elastomers, and synthetic fibers fall into these applications (Shrivastava 2018). SPs have a number of appearances, for example, in the manufacturing of corrective lenses, some transparent polymers may be formed into specific shapes. To be distorted from one form to another, the polymer rubber used in tires must be flexible enough (Ouellette and Rawn 2015).

17.3.1 Precise Classification of MPs and SPs

Plastics are widely classified as natural, semi-synthetic or synthetic depending on their source of origin. Natural polymers are classified as materials generally found in nature or derived from animals

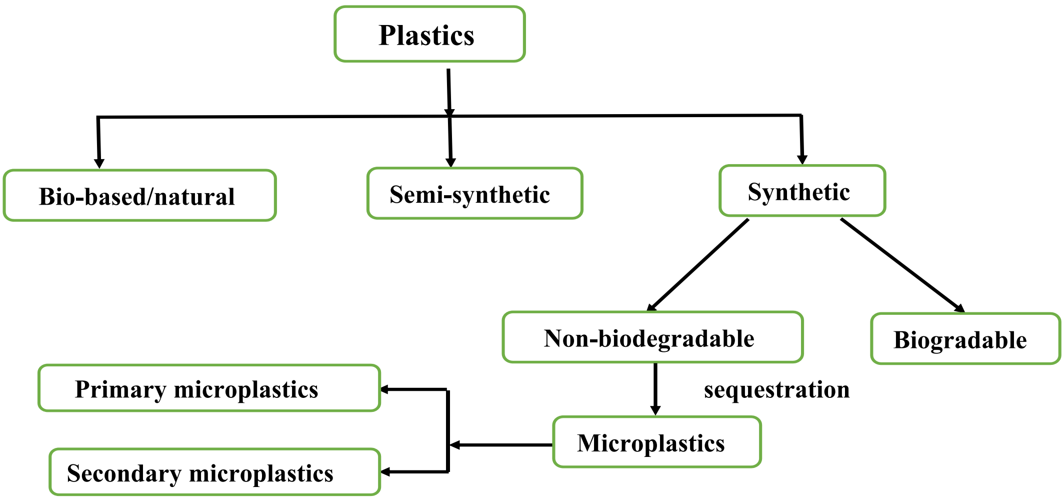

Fig. 17.2 Classification of MPs and SPs

and plants. Proteins and nucleic acids that exist in the human body, cellulose, natural rubber, silk, and wool are some examples of natural polymers. Semisynthetics polymers are the polymers produced by chemical modification of the natural polymers. Vulcanized rubber, cellulose acetate, and rayon are among the more popular ones (Shrivastava 2018). Again, SPs are classified into two groups, biodegradable and non-biodegradable polymers. Then non-biodegradable polymers sequestrate into MPs (Fig. 17.2).

Moreover, MPs are classified based on source as primary and secondary MPs (Duis and Coors 2016; Thompson 2015; Cole et al. 2011). Primary MPs are firmly formulated for uses, including medicine vectors, cosmetic abrasives, and applications of automotive and aerospace (Auta et al. 2017). Secondary MPs are derived from large plastics, in which they are increasingly broken into small sections by various, dynamic physical factors such as temperature, UV light, waves, and wind (Rocha-Santos and Duarte 2015).

17.3.2 Emission Sources of MPs in Soils

MPs enter the soil via mainly two sources such as direct and indirect source. In cultivation, plastic mulch products, greenhouse products and soil conditioners are direct sources. Indirect sources involve the use of wastewater, littering and biological substances (Duis and Coors 2016). In addition, MPs penetrate soil from numerous channels, including landfill sites, soil alteration, land application of sewage sludge, drainage, irrigation, compost and organic fertilizers, remnants of agricultural mulching film, tire wear and tear, and atmospheric deposition, etc. (Guo et al. 2020). Because of population size, resources, existence, and effectiveness of waste management activities, MPs emissions per capita differ significantly across countries (Ziajahromi et al. 2016; Nizzetto et al. 2016). In Europe, 63,000 to 430,000 tons per year of MPs were found in agroecosystems by biosolids alone, while 44,000 to 300,000 tons per year of the MPs were in North America (Nizzetto et al. 2016).

17.4 Exposure Routes of MPs and SPs in Soil

The prevalence of plastics in the world, whether as MPs debris or as MPs have been broadly recognized as a global issue (Gionfra 2018). Plastics are recalcitrant polymers released to the atmosphere by uncontrolled usage leading to accumulation and increased water and soil

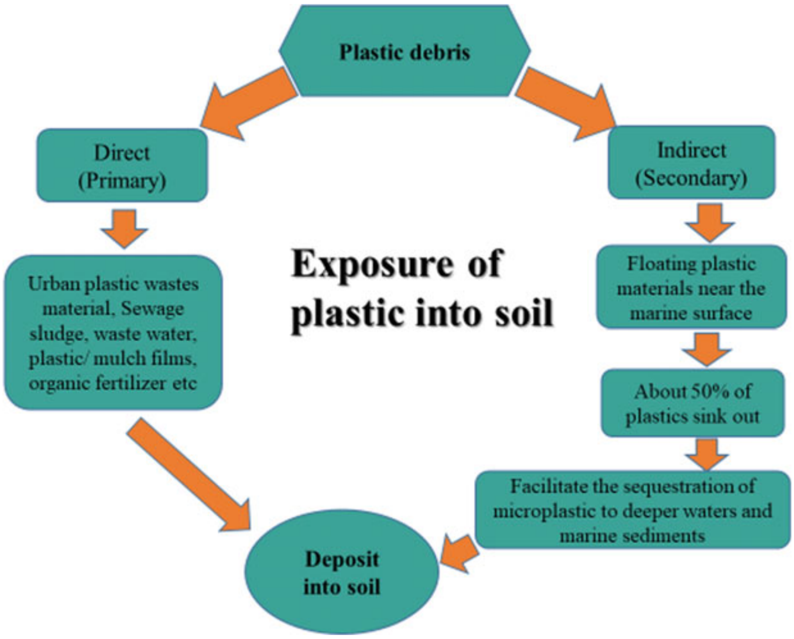

Fig. 17.3 Multiple exposure routes of MPs and SPs in soil

contamination. It consists of approximately 80% of the litter leads to accumulate in agricultural land, waste disposal, and water bodies. Therefore, plastics have a wide variety of uses extending from agricultural, commercial, and domestic applications. An example of common application in the agriculture sector involves polyethylene soil mulching (Iram et al. 2019). Since practices of recycling or otherwise handling plastic wastes have not been preserved, remaining plastic wastes have deposited in the environment (Awasthi 2020). Most of this waste is dumped near water bodies, in urban drainage systems, in which it flows into rivers and ends up in oceans in different types, such as MPs (particles of 5 mm in small fragments of large pieces of plastic) (Hale et al. 2020). Global production of plastics has reached alarming proportions; plastics were manufactured 322 million tons globally in 2015. In 2015, plastic waste produced 6.300 million tons, 9% of which was recycled, 12% burned and remaining 79% sent to spilled or to landfill sites (Gionfra 2018). A study estimated that a large amount (about 110 000–730 000 tons per year) of MPs were emitted to cultivated fields in North America and Europe (Awasthi 2020).

Argo plastics can leak via wind or river transport in the marine environment. Plastic and MPs contamination can be seen in the oceans more significantly. Furthermore, over 80% of plastic contained on the ground has been made, consumed, and removed from marine environments (de Souza Machado et al. 2018). The practices of urban wastewater treatment plants as irrigations on agricultural land are commonly used method and an important source of primary MP pollution of soil (Nizzetto et al. 2016). Nutrient combinations N, P and K are encapsulated in a nutrient tablet, a polymer coating. It is also a significant cause of contamination of MPs. The nutritional pill does not decay after the introduction of the nutrients. MPs can be released into the environment in two ways: direct or primary and indirect or secondary (Fig. 17.3). In primary way MPs are released into the environment from domestic goods, such as microbeads, direct depleting and inadequate wastewater treatment, e.g., losses through the waste collection, industrial spills or discharges from landfill places (Lechner and Ramler 2015). Secondary MP pollution causes, on the other hand, include deliberate statement (illegal dumping), untreated waste or accidental wounding (such as fishing gear) (Boucher and Friot 2017). During municipal waste collection, sorting, transport and waste disposal, MPs are released. Additional plastic products being used for agricultural purposes, which also reflect possible sources of MP contamination in soil, are bottles, wrapping and netting (Horton et al. 2017). The plastic mulching is used to cover plant, seedlings, and shoots by using plastic films on crops. Plastic mulches are usually consisting of polyethylene and it is not easily dissolved in the soil, which is connected to MPs residue deposition (Steinmetz et al. 2016).

Level of MPs in the oceans has been extensively studied. Agricultural overflow from drainage and farmland can result in involvement of agricultural plastics or sewage-sludge derived fibers and microbeads.

In the above circumstances, it can be said that MPs persistence within the soil is greatly related to the direct exposure of MP sources. For reducing the exposure of MP, recycling efficacy should be increased, and public awareness should be raised. By using biodegradable plastic, it could be helpful for reducing the presence of MP for long duration.

17.5 Biodegradation of MPs and SPs

The recycling process is currently growing, but since more additives are used in their processing, the recycling rates are very low in maximum plastic materials (Song et al. 1998). Compared to other waste management technology, biodegradation is consistent (microbial mineralization) (Schink et al. 1992). Biodegradation using microorganisms offers a simple method of cleaning such plastic residues. Microbial enzymes are used to manage pollutants and help to establish an ecosystem that is environmentally friendly (Pathak and Navneet 2017). Breakdown of macromolecular chains by microbes is termed as biodegradation (Agarwal 2020). By the biological activity upon a material that causes any physical or chemical alteration is known as biodegradation (Alshehrei et al. 2017). Hydrolysis is the most critical form of enzymatic polymer cleavage reaction (Artham and Doble 2008; Schink et al. 1992). Some microorganisms have shown the ability for biodegradation of plastic content (Table 17.1).

A few steps have been taken in the process of plastic biodegradation (Fig. 17.4) and could be defined by particular terms:

Biodeterioration describes the results of the physical and chemical deterioration of microbial populations and other decomposing organisms resulting in a gradual deterioration of the plastics with changes in their physical, mechanical, and chemical properties (Lucas et al. 2008; Iram et al. 2019).

Biofragmentation is the enzymatic activity which cleaves polymeric plastics by ectozymes or free radicals secreted by micro-organisms into oligomers, dimers or monomers (Lucas et al. 2008). The use of different enzymes released via the microorganisms, including lipase, proteinase K., hydrogenase etc. are involved in plastic biodegradation (Ghosh et al. 2013).

Microbial assimilation period resembles to the breakdown in previous stages of the low-molecular organisms, which have contributed to substantial gas evolution and mineralization (Harrison et al. 2018). Microbial cell membrane receptors recognize and activate certain dispersed molecules through the membrane to reach the cells. Increased bio-transformations of non-realizable plastic fragments by a cell membrane receptor lead to the generation of products that can easily spread into the cell (Lucas et al. 2008). Most cases can measure the stage rate by calculating the evolution of the gas or by growing the biomass of the selected microorganism, if carried out in a bioreactor (Harrison et al. 2018).

Plastics are being degraded very slowly. At first physical factors such as pH, temperature, and UV initiate this process (Devi et al. 2016). Biodegradability is also influenced by the chemical composition and source of the polymer (Muthu 2014). Microbes with different cleavage bond and enzyme activities achieve the process of

Table 17.1 Selected characteristics of the main commercial synthetic polymers along with microorganisms and enzymes involved in these polymers' biodegradation

Type of polymers	Name of plastics		Recycle ID code	Chemical formula	Structure	R group	Plastic Density ($g.cm^{-3}$)	T_m (°C)	Crystallinity (%)	Lifespan (year)	Uses of plastics	Microorganisms	Sources of microbes	Enzymes
Synthetic polymers (Microplastics)	Polyethylene (PE)	Low-density Polyethylene (LDPE)	4 LDPE	$(C_2H_4)_n$	Homo-polymer	Hydrogen	0.917–0.965	140–143	50	10–600	Squeezable Bottles, Frozen food bags, flexible container lids	*Rhodococcus rhodochorus*, *R. ruber* C208, *Staphylococcus epidermis, Brevibacillus borstelensis* 707, *Bacillus sp., Pseudomonas sp., Aspergillus sp., Penicillium funiculosum, Gliocladium virens, Chaetomium globosum, Pullularia pullulans, Fusarium sp.* AF4, *Tremetes versicolor*	Sewage treatment plants and waste management landfills, Dumping soil, Garden soil	Laccase, Alkane hydroxylase
		High-density Polyethylene (HDPE)	2 HDPE	$(C_2H_4)_n$	Homo-polymer	Hydrogen	0.917–0.965	140–143	50	10–600	Water, milk, and juice bottles, retail bags, and trash	*Amycolatopsis sp., Bacillus sp., Rhodococcus rhodochorus*, *Listeria sp., Micrococcus sp., Vibrio sp., Rhodococcus rhodochorus, Arthrobacter sp., Pseudomonas sp.,, Trametes versicolor, Phanerochaete chrysosporium* ME-446*Aspergillus sp.*	Garden soil, Mangrove soil	Manganese peroxidase

(continued)

Table 17.1 (continued)

Type of polymers	Name of plastics	Recycle ID code	Chemical formula	Structure	R group	Plastic Density ($g.cm^{-3}$)	T_m (°C)	Crystallinity (%)	Lifespan (year)	Uses of plastics	Microorganisms	Sources of microbes	Enzymes
	Polyvinyl chloride (PVC)	3 PVC	$(C_2H_3Cl)_n$	Homo-polymer	Chorine	1.16–1.58	115–245	0	50–100$_+$	Curtains, automobiles, bottles, raincoats, shoes soles, agriculture, electricity pipes, garden hoses	*Pseudomonas sp., Ochrobactrum* TD, *Aspergillus sp., Phanerochaete chrysosporium, Lentinus tigrinus, Thermomonospora fusca, Streptomyces sp., Poliporusversicolor, Phanerochaete chrysosporium* ME 446, *Pleurotus sp., Bacillus cereus, Acanthopleurobacter pedis*	Not reported	Not reported
	Polypropylene (PP)	5 PP	$(C_3H_6)_n$	Homo-polymer	Methyl	0.90–0.91	165	50	10–600	Bottle cups, straws, car seats, batteries, bumpers, syringes	Not reported	Not reported	Not reported
	Polyethylene terephthalate (PET) / Polyester	01 PET	$(C_{10}H_8O_4)_n$	Homo-polymer	Carboxyl and hydroxyl	1.37–1.45	280	0–50	450	meat package, carbonated soft drink bottle, clothing, food package, textile fibers	*Pseudomonas fluorescens, P. chlororaphis, P. putida, P. aeruginosa, P. protegens* BC2 12, *Ochrobactrum sp., Ideonella sakaiensis* 201-F6	Waste sites and dumping situations	Lipase, Poly-urethanase, Esterase, Protease, Hydrolases, Lipase, Cutinase

(continued)

Table 17.1 (continued)

Type of polymers	Name of plastics	Recycle ID code	Chemical formula	Structure	R group	Plastic Density (g.cm^{-3})	T_m (°C)	Crystallinity (%)	Lifespan (year)	Uses of plastics	Microorganisms	Sources of microbes	Enzymes
	Polyurethane (PU)	07 O	(R - (N = C = O)$_n$	Hetero-polymer	Isocyanate and polyol	1.20	400			Automotive, sponges, life jacket, clothing	*Aureobasidium pullulans, Rhodococcus equi., Pseudomonas sp., Corynebacterium sp., Bacillus sp., Arthrobacter globiformis, Aspergillus terreus, Curvularia senegalensis, Chaetomium globosum, Actinetobacter calcoaceticus, Actinetobacter gerneri* P7, *Fusarium solani, Rhizopus delemar, Comamonas acidovorans* TB-35, *Trichoderma sp., Pestalotiopsis microspore, Cladosporium sp.,*	Soil samples	Aryl acylamidase, Ureases, Esterases, Proteases, Lipase
	Polystyrene (PS)	6 PS	$(C_8H_8)_n$	Homo-polymer	Phenyl	1.04–1.1	240	0	50–80	Disposable cups, food packaging materials, laboratory ware, electronic device	*Actinomycete* sp., *Tenebrio molitor* (mealworm), *Exiguobacterium sp.* YT2, *Zophobas morio* (superworm), *Enterobacter sp., Citrobacter sedlakii, Alcaligenes sp., Brevundimonas diminuta, Pseudomonas putida* AJ, *Bacillus sp.*	Soil samples, Gut of mealworm, Rural market setting	Alkane hydroxylase

(continued)

Table 17.1 (continued)

Type of polymers	Name of plastics	Recycle ID code	Chemical formula	Structure	R group	Plastic Density (g.cm^{-3})	T_m (°C)	Crystallinity (%)	Lifespan (year)	Uses of plastics	Microorganisms	Sources of microbes	Enzymes
	Polycarbonate (PC)	07 O		Homo-polymer	Carbonate		52–150			Safety visor, lens in glasses, baby bottles, roofs	*Roseateles depolymerans* 61A, *Amycolatopsis sp.* HT-6, *Candida cylindracea*, *Chromobacterium viscosus*, *Pseudomonas sp.*	Not reported	Cholesterol esterase, Lipase, Lipoprotein lipase
	Polyamide (PA) / Nylon (NY)	07 O		Homo-polymer	Amide	1.13–1.35	190–276			Shoes, clothing, rainwear	*Agromyces sp.*, *Tremetes versicolor*, *Flavobacterium sp.*, *Pseudomonas sp.* NK87, White-rot fungus IZU-154	Soil samples, Compost and activated sludge	Manganese peroxidase, Nylon hydrolase, Laccase
	Polytetrafluoro-ethylene (PTFE)	07 O								Chemicals, electronics, kitchens utensils	Not reported	Not reported	Not reported
	Polymethyl-acrylate (PMA)	07 O	$(C_4H_6O_2)_n$			1.17–1.20					*Cyanobacteria*	Not reported	Not reported
References	Pathak and Navneet (2017); Devi et al. (2016); Siracusa (2019); Wu et al. (2016)	Devi et al. (2016); Wu et al. (2016)	Tokiwa et al. (2009); Wu et al. (2016)	Pathak and Navneet (2017)	Pathak and Navneet (2017)	Zhu et al. (2019); Glaser (2019; Horton et al. (2018)	Pathak and Navneet (2017); Tokiwa et al. (2009)	Glaser (2019); Ojeda (2013)	Glaser (2019); Ojeda (2013)	Siracusa (2019); Devi et al. (2016); Alshehrei (2017); Tokiwa et al. (2009)	Tokiwa et al. (2009); Glaser (2019); Devi et al. (2016); Iram et al. (2019); Fesseha et al. (2019) Pathak and Navneet (2017); Northcott and Pantos (2018); Wu et al. (2016)	John and Salim (2020); Tokiwa et al. (2009); Glaser (2019);	Iram et al., (2019); Fesseha et al., (2019); Wu et al., (2016); Tokiwa et al., (2009); Glaser (2019)

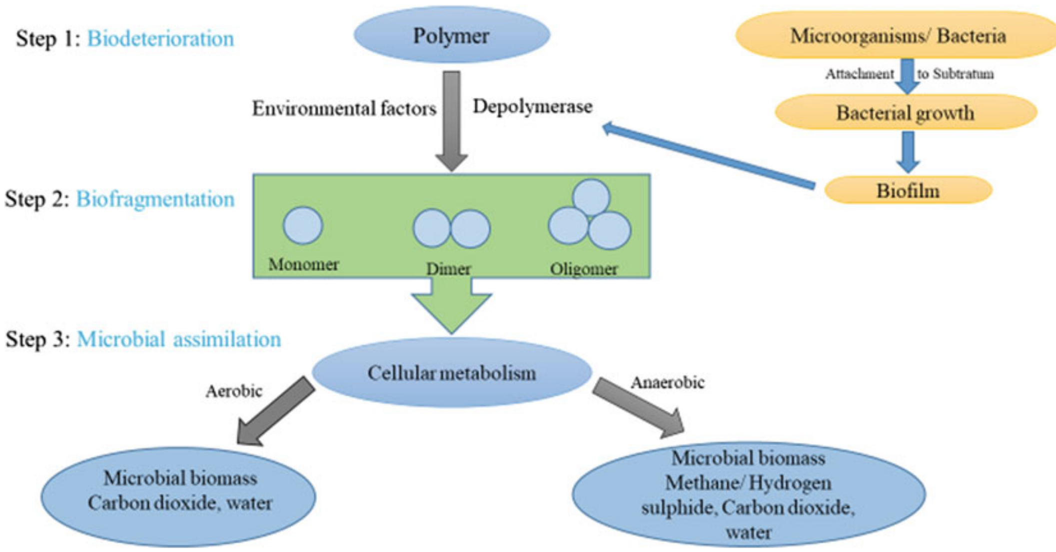

Fig. 17.4 The process of plastic biodegradation

degradation. Two types of enzymes are involved as extracellular and intracellular depolymerases (Dey et al. 2012). In the aerobic degradation process, oxygen is the necessary terminal electron acceptor. In addition, the production of CO_2 and H_2O occurs in aerobic conditions during plastic degradation due to cellular biomass of microorganisms (Glaser 2019). The aerobic system is more effective as compared to anaerobic conditions. The anaerobic method generates low energy due to the absence of O_2 when considering the energy output (Gottschalk 2012). The difference between anaerobic and aerobic degradation is very significant because the anaerobic conditions have been found to promote slower biodegradation kinetics (Glaser 2019).

C(plastic) + O_2 → H_2O + CO_2 + C(residue) + C(biomass) (Alshehrei 2017).

C(plastic) → CH_4 + H_2O + CO_2 + C(residue) + C(biomass) (Alshehrei 2017).

Alshehrei (2017) reported that biodegradation of polymers involves some steps as following:

1. The microorganism attachment to the surface of the polymer.
2. Development of the microorganism.
3. Ultimate degradation of the polymer.

The relation of the microorganism to the polymer's surface helps to produce biofilm (Pathak and Navneet 2017) (Fig. 17.2). For the degradation of the natural environment, biofilm formation is important (Sivan et al. 2006).

17.6 Analytical Methods of MPs and SPs in Soils

Analytical methods of MPs in soils comprise four steps- (a) extraction, (b) cleanup, (c) identification, and (d) quantification.

(a) Density fractionation methods during extraction procedure are extensively applied to abstract MPs from the soil complex matrix, since the density values of the frequently (0.8 to 1.4 gcm^{-3}) detected MPs are smaller than soil particles (2.6–2.7 gcm^{-3}) (Hidalgo-Ruz et al. 2012; Claessens et al. 2013; Hidalgo-Ruz et al. 2012; Scheurer and Bigalke 2018; Li et al. 2019). Pressurized fluid extraction (PFE) methods for extraction has several benefits including full automation, high efficiency, and low cost (Fuller and Gautam 2016; Li et al. 2019).

(b) Cleanup is a procedure which is used to eliminate SOM and/or other organic accessories from MPs. Currently applied cleanup procedures include peroxide digestion (H_2O_2), alkaline digestion (NaOH), and acid digestion (HNO_3, H_2SO_4) (Brady and Weil 2000; Zhang et al. 2018; Enders et al. 2017).

(c) Identification of MPs is generally based on the chemical and physical properties of isolated elements in combination with the subsequent extraction and cleanup steps. Consequently, the generally applied identification methods comprise of chemical identification and physical identification (such as mass spectrometry and spectral analysis) (Nor and Obbard 2014; Peng et al. 2017; Shim et al. 2017; Wang et al. 2019; Eriksen et al. 2013; Blasing and Amelung 2018; Paul et al. 2019; Shan et al. 2018; Corradini et al. 2019). MPs are identified by naked eyes based on the precise characteristics (shape, color, or surface texture). Dissecting or stereoscopic microscopy with image software are extensively applied for the smaller (i.e., < 1 mm) MPs in soils (Zhang and Liu 2018; Liu et al. 2018). Since visual sorting exhibits error rates of 20–70%, it is considered to be questionable (Eriksen et al. 2013).

(d) Quantification of MPs in soils includes weighing, counting, instrumental calculation, and mathematical analysis. Counting is the utmost applied quantitative method among them. Unfortunately, counting is a massive assignment (Li et al. 2019), yet weighing is more appropriate for soil samples with high MPs concentrations (Zhang et al. 2018). Mathematical analysis roughly calculates the mass of MPs in the soil. Additionally, some studies quantified MPs concentration in soils by using an instrument (e.g. vis–NIR, TGA-MS) (David et al. 2018; Li et al. 2019; Corradini et al. 2019).

17.7 Effect of MPs on the Soil Properties, Soil Biota and Plants

The presence of MPs could alter soil physicochemical properties such as water holding capacity, bulk density, nutrition contents, and soil structure (Rillig et al. 2019; de Souza Machado et al. 2018; Wan et al. 2018). Soil nature could influence the movement of MPs, and MPs alter the soil properties as soil function and structure as well as microbial composition/diversity, which lead to animal and plant values and current possible concerns for food safety and quality, eventually threatening human health (Table 17.2) (Rillig et al. 2019). MPs can increase water evaporation which may lead to soil drying, with possible negative values for plant

Additionally, fluctuations in the overall structure of soil affect the progression of soil accumulation such as affect root symbionts, including N-fixers and mycorrhiza, which change the microbial community composition in soil (de Souza Machado et al. 2018). Interestingly, plant activities comprehensively depend on the soil biota and their composition/diversity (Rilling et al. 2019). However, considering plants are a main constituent in terrestrial ecosystems and the occurrence of MPs, additional research should be comprised with the various types of plastic particles, soil conditions, and plant species, due to systematically assess the potential associations of MPs contamination to the agricultural soil (Wang et al. 2019). The collective effects of MPs and their related contaminants on the soil microorganisms are very few studied.

17.8 Techniques for Determining the Biodegradability of Polymers

Various techniques could be used in combination for determining the biodegradability of polymers (Raddadi and Fava 2019). These methods include visual observations, molecular weight measurement, physical property evaluation, chemical element analysis, gas formation study, radiolabeling, etc. These techniques are summarized in Table 17.3. The assessment of observable changes in plastics designate degradation which comprises of the formation of holes or cracks, de-fragmentation, roughening of the

Table 17.2 Effect of MPs on soil properties, soil biota and plants

Microplastic effects	Effects on the soil properties	Effects on the soil biota	Effects on the plants
	– Decline soil bulk densities which decrease infiltration resistance for better soil aeration and plant roots – Increase water evaporation – Affect the process of soil aggregation – Effects on soil fertility and nutrients – Increase the concentration of nitrogen, phosphorus and dissolved organic carbon (DOC) in soil – Play role in toxic concentrating chemicals such as heavy metals and hydrophobic organic contaminants on their surface – Stimulate the transport activities of chemicals – Increase the flexibility of organic contaminants in soil.	– Mycorrhiza and N-fixers affect the root symbiosis – Decrease soil enzyme activities (fluorescein diacetate hydrolysis and dehydrogenase), microbial biomass, and functional diversity with increasing concentrations of MPs residue – Influence in mortality – Reduction in growth rate – Increased Zinc exposure to earthworm –Reproduction inhibition – Gut damages – Decrease in body weight – Reproduction inhibition – Modifications in expression of genes	– Reduce the root and shoot biomass – Adversarial effects on wheat reproductive and vegetative growth – Modifications in leaf and root characters and biomass
References	Rilling et al. (2019); Guo et al. (2020); de Souza Machado et al. (2018); Wang et al. (2019)	Wang et al. (2019); Rilling et al. (2019); de Souza Machado et al. (2019); Ng et al. (2018)	Wang et al. (2019); Rilling et al. (2019); Li et al. (2019)

surface, and fluctuations in color or establishment of biofilms on the surface (Ikada 1999). Highly sophisticated observations could be needed to obtain the degradation mechanism information by using transmission optical microscopy, SEM or atomic force microscopy (Alshehrei 2017). Physical properties can be examined by using various methods, as for example: density and viscosity by HT-GPC, morphology by SEM, amorphous and crystalline region by X-ray diffraction, and melting and glass transition temperature by TG analysis (John and Salim 2020).

FTIR is used to determine the disappearance or formation of functional groups (Arutchelvi et al. 2008; John and Salim 2020). TLC, GCMS and NMR are used to determine the molecular distribution and weight of the degraded intermediates or products (Arutchelvi et al. 2008; John and Salim 2020). CO_2 evolution can be determined by Gas Chromatography (Hoffmann et al. 1997; Raddadi and Fava 2019). Radiolabeling technique is used as substrate for the development of microbial growth with carbon isotope ^{14}C for labeling the carbon in the polymer (Alshehrei 2017). Overall analytical methods

Table 17.3 Techniques for determining the biodegradability of polymers

Methods	Analytical approach	Comments	References
Visual observations	SEM, TEM, AFM	– Applied to designate degradation include the establishment of cracks or holes, roughening of the surface, changes in development or color, and de-fragmentation of biofilms on the surface – Used as indication of any microbial attack by visual changes of parameter	Alshehrei (2017); Ikada (1999)
Molecular weight measurement	TLC, GC, NMR, GC–MS	– Used to evaluate the change of polymer molar mass – Observed the distribution and molecular weight of the degraded intermediates or products	Arutchelvi et al. (2008); John and Salim (2020)
Physical properties evaluation	SEM, HT-GPC, X-ray diffraction, Thermogravimetric (TG) analysis	– Used to measure density, contact angle, melting temperature (T_m), viscosity, glass transition temperature (T_g), amorphous regions, and changes in the crystalline	Witt et al. (2008); John and Salim (2020)
Chemical element analysis	FTIR	– Used to analysis the disappearance or establishment of functional groups	Arutchelvi et al. (2008); John and Salim (2020)
Mechanical features query	Dynamic Mechanical Analysis	– Used to analysis elastic modulus, tensile strength, and elongation at break	Harrison et al. (2018); John and Salim (2020)
Gas formation (carbon dioxide and/or methane) study	GC, Titration with barium hydroxide	– Gives direct information on the polymer to metabolic product and the bioconversion of the carbon backbone	John and Salim (2020); Hoffmann et al. (1997); Raddadi and Fava (2019)
Radiolabeling	Not reported	– Applied as substrate for the development of microbial growth with carbon isotope ^{14}C for labeling the carbon in the polymer – The mineralization is distinguished by the measurement of radioactive gas ($^{14}CO_2$, $^{14}CH_4$) – Limited application due to the cost and difficulties of preparing the radioactive polymer – Need to specific measurement for the disposal and management of the radiolabeled samples	Raddadi and Fava (2019)
Metabolic activity estimation	Protein analysis, ATP assays, and FDA analysis	– Applied to screen microorganisms which may degrade a certain polymer	John and Salim (2020); Arutchelvi et al. (2008);
Other analytical techniques reported recently	RIfS	– Valuable method for the assessment dissimilarity to the physical thickness of biodegradable polymer	Raddadi and Fava (2019)

(continued)

Table 17.3 (continued)

Methods	Analytical approach	Comments	References
		– Applied for the observing enzymatic biodegradation of PCL – Not used in the circumstance of polymers/plastics.	
	EA/IRMS	– Applied for the assessment of carbon stable isotopes ($\delta^{13}C$) – It could be reflected the biodegradation of plastic material by increase of $\delta^{13}C$	

* FTIR: Fourier-transform infrared spectroscopy, GC: gas chromatography, NMR: nuclear magnetic resonance spectroscopy, GC–MS: gas chromatography with mass spectrometry, HT-GPC: high temperature gel permeation chromatography, FDA: fluorescein diacetate analysis, TLC: thin layer chromatography, SEM: scanning electron microscope, AFM: atomic force microscopy, TEM: transmission electron microscopy, RIfS: Reflectometric interference spectroscopy, EA/IRMS: Elemental analyzer/isotope ratio mass spectrometry

are generally applied for assessing the polymer biodegradation/conventional plastics with other techniques such as RIfS and EA/IRMS. On the contrary, EA/IRMS is a technique based on the assessment of carbon stable isotopes ($\delta^{13}C$) that reflect the biodegradation of plastic material by increase of $\delta^{13}C$ values (Raddadi and Fava 2019).

17.9 Factors Affecting Biodegradation of Plastics

Biodegradations of plastic are affected by numerous factors that comprise of microorganism's type, nature of pretreatment, and polymer characteristics. The characteristics of polymer include its mobility, molecular weight, crystallinity, substituent present, and functional groups existing in its structure. Table 17.4 summarizes the various factors that directly affect the biodegradation of MPs. Biodegradations of polymers are affected by two main factors, namely characteristic features of polymer and exposure condition. Exposure circumstances are further classified as biotic and abiotic factors. Microorganisms can enhance the degradation of MPs, which is pronounced implication to combat MP pollution (Devi et al. 2016). For example, *Zalerion maritimum* reveals high removal productivities of MPs; but *Nia vibrissa* showed lower biodegradation productivities under the similar circumstances (Shen et al. 2019).

Abiotic factors such as pH, moisture, and temperature affect the hydrolysis reaction rates through degradation (Iram et al. 2019). The high moisture content and temperature increase in microbial activity and hydrolysis reaction rates (Devi et al. 2016). The kinetics of polymer degradation rely on several environmental factors such as humid air, dry air, a landfill, soil, freshwater, sewage, a marine environment, or a composting environment (Fesseha et al. 2019). Configuration plasticity plays a significant role in polymer biodegradation (Iram et al. 2019). The high plasticity of polymer has high accessible for microbes. Nevertheless, the copolymer biodegradability depends on the comonomer types (Devi et al. 2016). Among the factors affecting biodegradation of plastics, the presence microbial species and plastic properties play a crucial role in MPs biodegradation.

17.10 Strategies to Resolve the Question of MPs

Strategies to resolve the problem of MPs pollution could be focused on the cleanup, source of remediation, and control. Questions of concern are pointed below-

(1) Plastic products should be banned to eliminate the main source of MPs.
(2) Applicability of biodegradable materials. The highest eco-friendly and creative method is to practice biodegradable plastics. Both

Table 17.4 List of several factors affecting biodegradation of plastics

Factors		Remarks	References
Biotic	Microbial species	Presence of suitable microbial species can initiate the biodegradation process	Shen et al. (2019)
	Extracellular enzymes	Different microorganisms are produced extracellular enzymes which may have active sites and may able to biodegrade polymers	Devi et al. (2016); Shen et al. (2019)
	Initial biomass	Initial biomass is one of the key players of plastic biodegradation	Shen et al. (2019)
	Biosurfactants	The biodegradation process is enriched by the accumulation of biosurfactants.	Iram et al. (2019)
Abiotic	Temperature	Changes the temperature increase/decrease the microbial activity and hydrolysis reaction rates	Devi et al. (2016); Iram et al. (2019)
	Moisture	Hydrolytic movement of microorganisms is enlarged with changed of moisture content	Iram et al. (2019)
	Oxygen	Sufficient amount of oxygen should be present in usable form	Kumar et al. (1982)
	pH	pH affects the rate of degradation and alters microbial growth rate	Iram et al. (2019)
	UV radiation	The ultraviolet (UV) radiation acts a significant role in initiating weathering such as mechanical stress with cracking and stiffening	Devi et al. (2016); Glaser (2019)
	Nutrients	Even if the polymer acts as the source of sole carbon, but other vital elements are needed for microbial usage	Kumar et al. (1982)
	Infrared radiation	Near infrared and visible radiation may contribute to the weathering procedure of biodegradation	Glaser (2019)
	Additives, impurities and intermediate products	Biodegradation processes are exposed to inhibit by a variety of agents such as impurities, additives, and intermediate products which can prevent or retard degradation	Kumar et al. (1982); Devi et al. (2016)
Plastic properties	Shape	Polymers are easy to degrade by enzyme in large surface area	Iram et al. (2019)
	Molecular weight	Biodegradability decreases as the molecular weight increases	Iram et al. (2019); Devi et al. (2016)
	Density	Plastics having lower density degrade faster than higher	Fesseha et al. (2019)
	Functional groups	The availability of functional groups increases hydrophobicity	Fesseha et al. (2019)
	Hydrophobicity	Hydrophilic degradation is quicker as compared hydrophobic	Shen et al. (2019)
	Molecular chain branching / Structural complexity	Biodegradation is inhibited by molecular chain branching	Kumar et al. (1982); Fesseha et al. (2019)
	Molecular bonds	Occurrence of simply breakdown bonds as like amide or ester bonds (ester > ether > amide > urethane)	Fesseha et al. (2019); Alshehrei (2017)
	Crystallinity	Polymer crystallinity can play a strong role. An amorphous region of polymer plastic degrades faster than crystalline	Devi et al. (2016); Fesseha et al. (2019)
	Blend	Molecular compositions of plastic material affect biodegradation	Devi et al. (2016)
	tacticity	The stereochemical arrangement of polymers has dramatic effects on the physical properties of the polymer	Devi et al. (2016)
	Comonomers	Accumulation of comonomer into polymer structure improved the abnormality of the polymer chain	Devi et al. (2016)
	Physical form	Nature and physical structure of the polymer (e.g. powder, pellets, films, or fibers)	Fesseha et al. (2019)
	Melting point	Enzyme proficiently degrades at low melting point. But high melting point, polymers are less degraded	Iram et al. (2019)
	Hardness / flexibility	Soft polymers degrade faster than hard ones	Fesseha et al. (2019)

fossil-based and bioplastics can be proficiently degraded. Microbe development and active enzymes can degrade plastics with high value compounds.
(3) Improved reuses recycle and recovery of plastics. Biodegradable/biocompatible plastics as like poly-hydroxyalkanoates (PHA), polylactatide (PLA), and others are commercially accessible which may substitute traditional plastics.

(1) Upgraded separation proficiency at wastewater treatment plant (WWTP). The ability of current WWTP should be promoted to eliminate MPs skillfully and to avoid MPs from the incoming surface, for example, ocean, river, and so on.
(2) Development of bioremediation and cleanup skills. Besides, worldwide collaborations are required to clean up the plastic remains from the ocean, which decrease the main source of ocean MPs. Forthcoming study should be required to develop the approaches for in situ biodegradation of MPs by improving natural attenuation, by adding of microorganisms or by using native microflora.

17.11 Knowledge Gaps and Future Research Challenges

Based on this review, the understanding of MPs in agricultural soil is progressing, but there is a notable deficiency of the appropriate information. Despite progress in the identification, measurement, and isolation of MPs in agricultural soil, there are still numerous scientific difficulties existing. Here, we highlighted some key knowledge gaps that are essential to be followed;
(1) The characteristics of MP pollution in agricultural soil, sustaining mechanisms of toxicity and their possible ecological effects should be broadly studied in the future.
(2) Very few researchers have studied the MPs exposure and their effects on reproductive and vegetative growth of a few plants, whereas more than 200,000 plant species are present worldwide.
(3) There is a need to study how plants can accumulate MPs from the soil.
(4) More scientific studies are needed regarding the effects of the MPs on human health.
(5) Additionally, it should produce high-value compounds, synthetic biology to generate microorganisms from plastic waste by improving circular use of plastics.
(6) Future research should be focused on monomers and oligomers formed from MPs.

17.12 Conclusion

MPs are tiny, heterogeneously mixed plastics that are ubiquitous in arable soils, entering soil environments through sewage irrigation, agricultural mulching films, landfills, and other outlets. Some factors, such as soil characteristics and soil biota, affect the horizontal and vertical movement of MPs in the agricultural soil, and MPs modify the soil structure when they are mixed into soil aggregates. MPs are also capable of interacting with other factors such as impacting soil function and health, and have higher adsorption potential for harmful pollutants, exacerbating soil contamination and increasing antagonistic effects on microorganisms and human health. Additionally, MPs are readily consumed by soil organisms due to their minor size and pass through the food chain; the absorption of MPs cause both physiological and mechanical destruction. MPs also have possible effects on the plant growth where MPs can transport and accumulate in plants. Here, we suggest many areas of the soil MPs for future study, and possible remediation steps are immediately required to moderate the hazard factors by MP contamination. Bioremediation of MP-polluted soil is a promising and environmentally sustainable measure. The application of biodegradable plastics, genetically modified organisms, and changes in industrial degradation facilities should be encouraged to ensure environmental protection and sustainability.

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