Harnessing microbes for degrading synthetic plastic: a review

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Abstract

Engineered plastics are vital in our present life and hence, its gathering is a significant worry for climate human wellbeing and planet's maintainability. It is urgent now to build up a creative methodology for removal of plastic waste. The goal of this review is to layout the advances made in microbial degradation of manufactured plastic and outlining the compounds associated with biodegradation. We have summarized the role of microorganisms and enzymes that can corrupt an assortment for the most part utilized manufactured plastics like polyethylene (PE), polystyrene (PS), polyurethane (PU), polyvinyl chloride (PVC) and polyethylene terephthalate (PET). In spite of the fact that there are various plastic removal techniques however, every one has its own inborn restrictions, yet biodegradation is by all accounts the most un-hurtful strategy to manage this sort of toxin. The current understanding of the roles played by microorganisms and their compounds in improving the corruption of engineered plastics are reviewed with center around their method of activity and the enzymatic components. These discoveries will contribute to fabricate an origination ofbio up cycling plastic wastes by associating the biodegradation of plastic waste and biosynthesis of significant items in microorganisms.

I. Introduction

Plastics are adaptable strong materials which are solid, light weight, dampness safe and tough. It has numerous applications and on the grounds that it is hard to corrupt, the climate contamination and risks are expanding step by step (Thompson et al 2009). They have enormous aggregation in city waste frameworks because of which tiny and nano measured particles are presently showing up in both earthly and aquatic ecosystems (Albarez – Hernandez et al 2019, Bergmann et al 2019). Various plastics have distinctive compound construction , on that premise they are described as high thickness polyethylene (HDPE), low thickness polyethylene (HDPE), polypropylene (PP), polystyrene(PP), polyethylene(PE) and polyethylene terephthalate (PET) .They have wide applications in modern areas, homegrown market and in horticulture areas (for instance – utilization of plastic soil mulching) (Sivan 2011). It has been told by R. gayer et al in 2017 that approx. 7 billions of plastic end up in ocean consistently. Late records of 2017 showed that people produce 8.3 huge loads of plastic in a year. Plastic creation increments up to three hundred and eleven million tons all around the world in 2014 (Urbanek K Alauzet N et al 2018). Around 80 % of plastic waste across worldwide is comprised of manufactured plastic which incorporate polyethylene, polyethylene terephthalate etc. (Wilkes RA, Aristilde 2017). Right now utilized plastic are additionally the most ordinarily engineered polymers got from petrochemical based hydrocarbons (2017). Plastics for the most part are grouped in two classes-biodegradable and non-biodegradable plastics. Biodegradable plastic enrich the soil by returning it by the interaction of polypropylene, polystyrene and polyvinylchloride (Ahmed et al 2017). It was found by Ahmed T in 2018 that utilization of microorganisms having the capability to produce exoenzymes under pressure conditions can degrade the biodegradable polymers for ex- microscopic organisms and parasites. Several microbes including bacteria and fungi have been found till now that can possibly corrupt oil based plastic in lab condition. Microbial debasement of plastic by enzymatic methods is an approach to depolymerize waste petro plastic into monomers with related creation of higher worth bio items (Montazer et al 2019, 2020). Assortment of microbial stains has been discovered that separates plastic polymers into monomers.Microbes produce extracellular catalysts that have dynamic destinations with different shapes and sizes that assist in degrading some specific polymers. Degradation of miniature plastic is an integrated cycle of physiochemical and microbial corruption factors .Microbes can receive themselves to each climate conditions and can possibly degrade a few mixtures for e. g – miniature plastic (Streams and Beet 2012, Krueger et al 2015). It is critical to perform screening of plastic debasing microorganisms to distinguish the depolymerase and other key chemicals that are included in plastic corruption (Jiakang RU et al 2020). Park n Kim (2019) studied that organisms that live in conditions polluted with miniature plastics have an adjusted digestion and their capability to corrupt polymer is high. Variety of microorganisms have been isolated from various sources such as soil of plastic dumping site, sewage ,mulch films, landfills, marine water and guts of plastic eating worms that are competent to degrade different kinds of plastics (PP,PVC,PET,PP) in their own way (Yang et al 2014,2015). The debasement of polymer relies upon the nature of polymer and the condition it is exposed to corrupt; going from abiotic factors (sun ,light ,humidity)to digestion by organisms (microbes and parasites) (karamanglioglu 2017). Abiotic degradation is additionally named deterioration brought about by climate factors like UV illumination, temperature, wind, and waves while biotic corruption likewise named debasement brought about by the activity of microorganisms. Both corruption measures act all the while in nature and the organisms involved in it eaten up the polymer and changes its properties (Restrepo-florez et al 2014).

II. Biodegradation of synthetic plastic

Plastic biodegradation is the change of intractable waste to non-poisonous lower sub-atomic mass mixtures which can return into biogeochemical cycle. Modification in the actual properties of the polymers particularly by atomic weight decrease, loss of mechanical strength and change in plastic surface properties can be seen by the biodegradation of plastic (Ho et al 2018). Biodegradation is influenced by a few variables, from the sort of microorganism to the kind of polymers, their physicochemical properties, and the climate conditions (e.g., temperature, pH, UV radiation). Biodegradation is a complex measure which is subjected to a few variables, like accessibility of a substrate, surface attributes, morphology, sub-atomic load of the polymers and in this way, a precise meaning of biodegradation is missing (Harrison et al, 2019). Biodegradation of certain kinds of polymers utilizing various microorganisms, biofilm shaping microbes, bacterial consortia, and parasites are specifically compelling in the biodegradation of characteristic and engineered polymers (Rujni'c-Sokele and Pilipovi'c, 2017).The cycle of biodegradation of plastic includes four stages i.e. biodeterioration, biofragmentation, digestion and mineralization (Figure 1).

2.1 Biodeterioration-the physical and synthetic activity of organism or whatever other natural biological agentthat brings about the external degradation of plastic polymer just as well as alteration in the physical, compound and mechanical properties of the polymer is called as biodeterioration. Formation of biofilm is important to build the polymeric surface communication with microscopic organisms in the event of polyethylene biodeterioration (Schwibbert et al 2019). *Pseudomonas* can be seen as biofilm framing microbes that can adhere more strongly and debase low thickness polyethylene in contrast with different microscopic organisms (Tribedi et al 2015).

2.2 Biofragmentation-It is a depolymerisation step which includes the activity of extracellular proteins that cause the synergist cleavage of crumbled plastic polymers into more modest units and produce free radicals by organisms (Jenkins et al 2019).The biofragmentation step includes two primary responses: decrease in polymer atomic weight and oxidation of lower sub-atomic weight particles. These responses help in the ensuing activity of microbial enzymatic frameworks (Restrepo-florez et al 2014). It is assumed that different organic and inorganic compounds released by microbes could be significant in facilitating the biofragmentation process.

2.3 Assimilation –During the step of osmosis, the lower atomic weight compounds that are created during biofragmentation are moved into the microorganism cytoplasm. It includes both active and passive transportation. Shahnawaj et al (2019) showed that a degradative result (octadecone) of plastic polymer has been taken up in higher concentration by the *Pseudomonas sp. strain DG17* through facilitated transport system while it is assimilated through energy dependent active transportation when in lower concentration.

2.4 Mineralization-The plastic subsidiaries go through arrangement of enzymatic responses which cause their total debasement into oxidized metabolites including CO_2, N_2, and CH_4 AND H_2O (Ho et al 2018). The cycle of mineralisation could be oxygen consuming or anaerobic however in both case it requires the contribution of different proteins which incorporate esterase, lipase, cutinase, peroxidase and laccase (Alshehrei 2017). The total minerlisation of plastic polymers has been appeared by strategies, for example, isotopic tracing and the evaluation of CO2 discharge utilizing Strum's technique (Yang et al 2020).

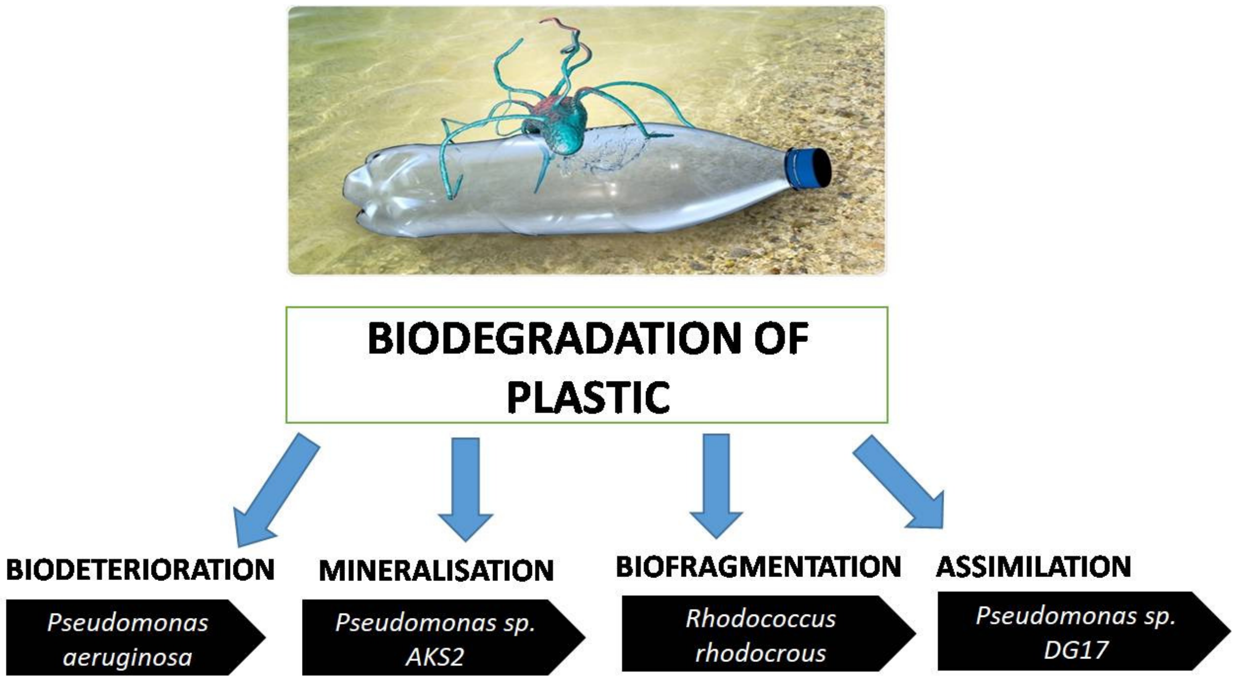

Figure 1. – Methods of Biodegradation of plastics

III. Microfloral diversity for plastic degradation

Microorganisms of all classes are in forefront of blocking the bioaccumulation of different natural and inorganic mixtures in the climate. Different microbial networks have been seen as possible degradative during manufactured plastic corruption, depend on their capacity to adjust and utilize these synthetic compounds as substrate for their energy and development (Figure 2). Different classes of organisms including bacteria, fungi as well as enzymes have been examined having the capacity to biodegrade different manufactured plastic polymers. These microorganisms use their different enzymatic frameworks to corrupt the polymer into intermediates which further can be metabolized for their energy needs (Ayodeji amobonye et al 2020). The rate of engineered polymer debasement by different microorganisms is generally lethargic hence it isn't feasible for constant modern applications. This had lead to the search for dramatic development of bioplastic with better biodegradability possibilities (Thiruchelvi et al 2020). Several Actinomycetes including the *Streptomyces* bunch, *Rhodococcusruber, Actinomaduraspecies*, and the *Thermophilic Thermoactinomyces sp*. have been secluded from various biological zones and found to have huge plastic biodegradation possibilities (Auta et al 2018,Fabloune et al 2020).They have produced a wide range of hydrolytic catalysts just as other bioactive metabolites that have been demonstrated to be a significant factor in the actinomycetal colonization of plastics (Gilan and Sivan 2013). Different bacterial species from the *Pseudomonas, Bacillus and E.coli* genera have been found with momentous potential to debase plastic polymers which have been found from various natural climates (Ayodeji et al 2020). Microorganisms have the capacity of biofilm development that assumes a critical part in the bacterial decay of plastics since it advances the adherence of the bacterial provinces to the plastic surface and their tirelessness (Puglisi et al 2019). Microbes of various classes including *Bacillus, Micrococcus, and Pseudomonas* have been appeared to debase different thermoset plastics, basically polyurethane. Fungi have additionally been found to possibly corrupt different plastic polymers and use these engineered polymers as the sole carbon or fuel source. Some contagious gatherings discovered to be generally most prominent with respect to engineered plastic biodegradation. It includes*A.clavatus* (Gajendiran et al 2016), *A. fumigatus* (Osman et al 2016) and *A.niger* (Usman et al 2020) that were confined from various earthly natural surroundings. Fungal biodegradation of plastic is upgraded by pretreatment of various substrates like photo treatment and temperature (Corti et al 2010) and different added substances (Jeyakumar et al 2013, Sancher 2020).

Various catalysts have been segregated as plastic corrupting compounds that are engaged with the organic debasement of polymers. These catalysts depolymerize the long binds of plastic polymers to a combination of oligomers, dimers and monomers. An assortment of proteins including lipase,esterase,laccase,peroxidase urease and proteases have been segregate from bacterial and parasitic sources that have been found to have PU corrupting capacities (Magnin et al 2020).A huge extent of intracellular enzymes is liable for the aerobic and anaerobic cycles important to change the intermediates to compounds which can be absorbed by the microbes (Pathak 2017).

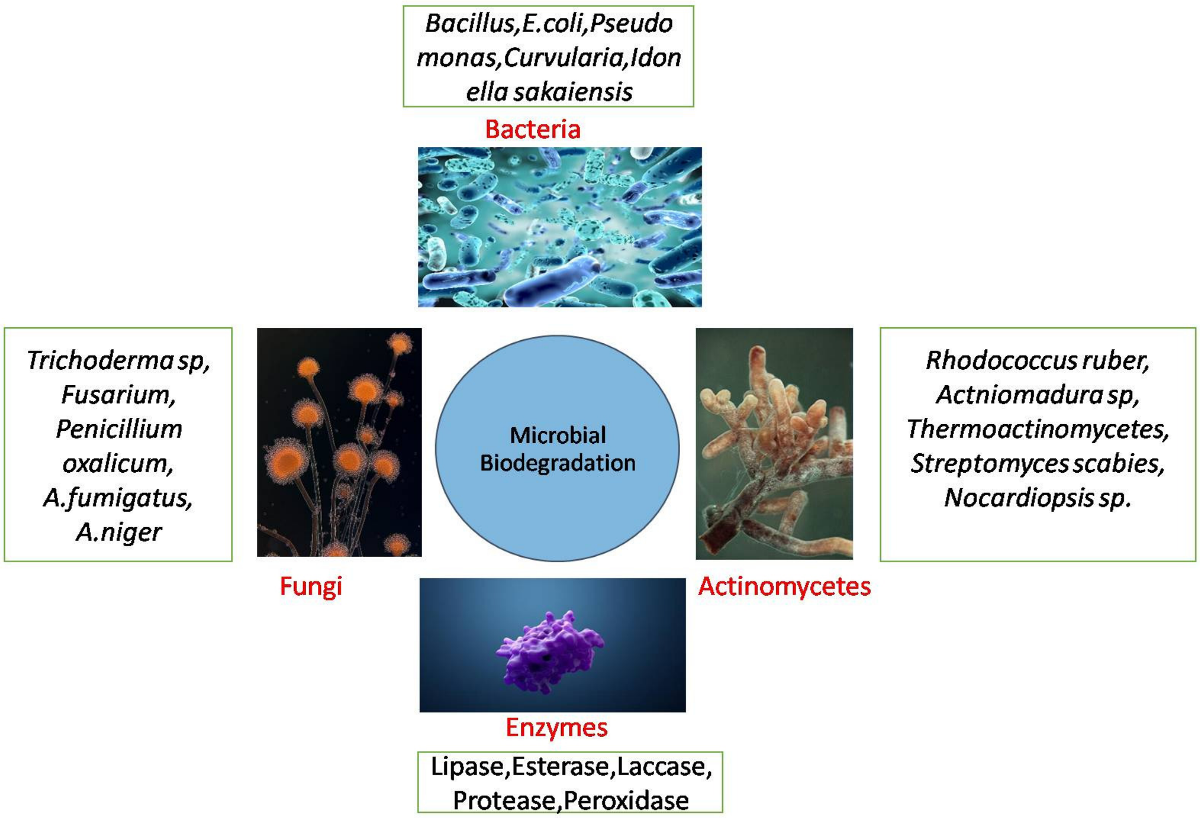

Figure 2. - Microflora enriched with plastic degrading capacity

III. Synthetic plastics and microbial biodegradation

As of now, there are just about 20 different gatherings of plastics have been found those have different evaluations and characteristics (Anna Williams). Plastics can be created through natural or inorganic crude materials or can be made through hydrocarbon monomers by altering common materials synthetically. The standard plastics that overwhelm the world market are : polypropylene (PP) 21.1% , polyethylene (PE) ; low thickness polyethylene (LPDE) 19.9% , high thickness polyethylene (HDPE) 16.1%, polyvinyl chloride (PVC) 11.8% ,polyethylene terephthalate (PET) 10.2% ,polyurethane (PU) 8.4% and polystyrene (PS) 7.8% (Geyer et al 2017). In recent years different researchers report several microorganisms and enzymes responsible for degradation of a class of synthetic plastics (Table 1).

3.1 Polyethylene (PE)

This plastic is considered as the essential design of any polymer and it includes the most popularized group of alkanes. PE is a direct hydrocarbon polymer comprised of long chains of ethylene monomers $(C2H4)$ n (Huerta et al

2018). It has been arrived at a broad use in food and drinks during the 1950s (Bardaji et al 2020). LPDE is discovered to be impervious to acids, bases, alcohols and esters yet it is unstable within the sight of solid oxidizing specialists, aliphatic and fragrant hydrocarbons (Scalenghe 2018). Microorganisms have been seperated from soil, ocean water, manure and actuated muck that have the ability to hydrolyze PE. Microorganisms have additionally been found in the gut of the more noteworthy wax worm, *Galleria melonella* that have a similar capacity of polymerizing PE(Bombelli et al 2017, Cassone et al 2020). Santo et al (2013) tracked down that the PE corrupting bacterium *Rhodococcus rubber C208* discharge extracellular laccase that could oxidize the PE films and produce carbonyl groups and decrease atomic weight. Microbial corruption of polyethylene has been seen in various species of Pseudomonas: *Pseudomonas aeruginosa PAO1, P. putida, P.aeruginosa ATCC, P.syringae* (Kyaw et al 2012), *Pseudomonas species E4* (Yoon et al 2012) and some others, for example, *Acinetobacter pitti IRN19*, *Micrococcus luteus IRN20*(Montazer et al 2019) and in bacterial strains from the genera comamonas, delftia and stenotrophomonas (Peixoto et al 2017). Bio osmosis and bio fracture has been accounted by Montazer et al in 2019 by bacterial species *P. putida LS46*, *Micrococcus luteus IRN20*and*P.putida IRN22*. These species had the option to use the untreated LDPE as a sole wellspring of carbon and energy for their development and create alkane hydrolysis items.

3.2 Polystyrene (PS)

It is the most plentiful plastic that is created worldwide and it is generally made into bundling material for food and removal dishware (Plastic Europe, 2018). This homopolymer is made by the polymerization of styrene monomers. The unadulterated strong state type of polystyrene is rapid, hard and has restricted adaptability (Mckeen 2014). PS are exceptionally impenetrable to biodegradation and are incredibly polymer having high atomic weight and solid hydrophobic character (Ho et al 2018). It was discovered that *Rhodococcus ruber C208*, actinomycetes, had the option to use PS to utilize it as sole carbon source for their development and had showed a weight reduction of 0.8% in about two months (Mor and Sivan 2008). Shimpi et al (2012) tracked down that an unadulterated strain of *P. aeruginosa* corrupt the adjusted PS and species from curvularia was explored for debasement of a tactic PS, with no pretreatment (Motta et al 2009). Debasement of Styrofoam (PS froth) up to half were accounted for during 24 hour by mealworms (hatchlings of *Tenebrio Molitor*) ,and this was upheld by decrease in atomic weight, change in substance arrangement and isotopic change after section through the intestinal parcel (Yang et al 2015). Xu et al (2019) had exhibited the biocatalytic instrument of polyethylene and polystyrene. Bacterial societies of *Exiguobacterium species strain TY2*, disconnected from the gut of *T.molitor* hatchlings was discovered to be PS corrupting (Yang et al 2015b) and strain of *Pseudomonas aeruginosa strain DSM 50071* was from *Z.atratu*s (Kim et al 2020). Jeon n Kim, 2015 had showed that both laccase and oxireductase can be engaged with the biodegradation of PS, for example, ALK hydroxylase and hydroquinone.

3.3 Polypropylene (PP)

It was discovered that dirt of a plastic unloading site contain three bacterial and two contagious strains that could use PP as their carbon source for development and debase 0.05-5% of PP after hatching for a year (Arkatkar et al 2010, Jeyakumar et al 2013). Two marine microscopic organisms have been separated from mangrove climate*; Bacillus species strain 2T* and *Rhodococcusspecies strain 36*, ready to fill in watery engineered media that contain miniature plastics and cause a weight reduction of 4.0-6.4% following 48 days (Auta et al 2018). *Stenotrophomonas panacihumi PA 3-2* is a mesophilic strain that was disengaged from soil of an open stockpiling yard for civil strong waste was accounted for to corrupt low atomic weight polypropylene and high sub-atomic weight polypropylene (Jeon and Kim 2016). Four bacterial strains of blended consortia were confined from waste management landfills and sewage treatment plants were additionally ready to debase PP strips and pellets and cause a weight reduction of 44.2-56.3% following 140 days (Skariyachan et al 2018). Physiochemical pretreatments on PP like gamma radiation, UV light, thermo oxidation and mix with degradable added substances could encourage the microbial corruption polypropylene.

3.4 Polyvinylchloride (PVC)

PVC is delivered as an item by polymerization of the vinyl chloride monomer (VCM) as during the time spent creation of PE, PP and PS. It has the most noteworthy extent of plasticizer among any remaining sorts of manufactured plastics. Giacomucci et al (2019) tracked down that bacterial strains detached from garden soil, landfill leachate, garbage removal locals and marine conditions answered to have the option to debase the plasticized PVC. A few contagious strains additionally been discovered that showed the capacity to crumble the plasticized PVC ,those were confined from different ecological samples, plasticized PVC sheets covered in the meadow soil (Ali et al 2014) and plastic garbage removal locales (Khatoon et al 2019). Two bacterial species*; Pseudomonas citronellolis* and *Bacillus flexus* have additionally been found to biodegrade polymer chains (Giacomucci et al 2019). These strains have been found to cause a lessening in mean atomic load of the PVC film by framing a thick biofilm on the plastic surface. Biofilm development and diminished atomic weight announced as polymer chain biodegradation (Wilkes and Aristilde 2017, Ahmed et al 2018).

3.5 Polyethylene terepthalate (PET)

This plastic is shaped by the polycondensation of terepthalic corrosive (TPA) and ethylene glycol or by dimethyl terephthalate and ethylene glycol transesterification (Hiraga et al 2019). In 2013, the overall creation of PET accounted to 56 million tones (Neufeld et al 2016). Focusing on enzymatic debasement of PET, Kawai characterized those hydrolases catalyst that have moderate surface hydrolyzing capacity as PET surface-adjusting proteins (Kawai et al 2019). He likewise found that *Humicola insolens* (Hic) presently named as *Thermomyces insolens*cause 97% weight reduction of ICPET films (7%) at 70% inside 96 hour. Under this thermophilic temperature, the polymer chains in the amorphous PET increase sufficient mobility to get to the dynamic destinations of PET hydrolases (Kawai et al 2019). Yoshida in 2016 have discovered that bacterium *Ideonella Sakaiensis 201-F6* can depolymerize PET polymers and use terephthalate subunits as a carbon fuel hotspot for digestion and development (Yoshida et al 2016). A catalyst glyoxylate carboligase (gcl) operon in a designed *P. putidaKT2440* (AT47054) strain has been accounted for in development increment and ethylene glycol usage upon overexpression (Franden et al 2016). This designed strain empowers change of ethylene glycol to medium chain length polyhydroxyalkonates (mcl-PHAs) (Mohanan et al 2020). Recombinant *Thermofibidafuscacutinase* communicated by *B. subtilis* has been appeared to debase the IcPET films (7%) with a weight reduction of upto 97.0% inside 120 hour at 70degreeCelsius (Wei et al 2019).

IV. Novel plastic degrading microbes

Among the different industrially accessible manufactured polymers, polyethylene (PE) is irrefutably the most used. Practically 40% of its complete creation is assigned for single use bundling (D.S. Green, B.Boots et al 2015) highlightening the significance of plastic removal as a worldwide issue. An examination has been performed on Brazilian Cerrado soil microbiome that permitted the disconnection and recognizable proof of nine novel bacterial strains fit for corrupt PE. Cerrado soil microbiome has diverse climate that has remarkable variety of metabolic responses recommending the presence of organisms capable for debasing a wide scope of substrates (A.Pereira, M.R.Sartori et al 2016). They observed bacterial strains which were from the genera *Comamonas*, *Delfitia* and *Stenotrophomonas* which showed metabolic action and cellular feasibility following 90 day incubation with PE as the sole carbon source. Overall, *Delfitia* sp. seems to have the most elevated debasement capacity followed by *Comamonassp*. and *Stenotrophomonassp*. FTIR information uncovered the unmistakable systems utilized by the strains to debase PE, which is confirmed by contrasts in wave numbers and forces of the adsorption tops (Juliana Peixito et al 2017).Another investigation has uncovered two novel strains from *Arthrobactersp*. and *Streptomyces* sp. that were detached from horticultural soil appeared to develop on PE film as a sole carbon source. *Arthrobacter* sp. chiefly filled in the suspension period of the way of life and *Streptomycessp*. shaped significant biofilms on the outside of the PE films. These strains were of various metabolic sorts and involved diverse microenvironments with differentiating healthful access and had a lot more prominent impact on biodegradation properties(Ya-Nan Han et al 2020).

V. CONCLUSIONS

This is an era of plastic and the interest in plastic is an expanding pattern. For the corruption of plastic, biodegradation is a viable technique. This paper has highlighted critical examinations on the biodegradation of manufactured plastic waste by organisms including *Actinomycetes*, fungi, microorganisms and enzymes. It is additionally accepted that the use of various microorganisms as a consortium will prompt more prominent proficiency in plastic degradation because of the synergism among microorganisms and their enzymes. This understanding will be useful in the changes of enzymes with better corruption effectiveness as well as an advancement of novel plastic polymers with improved biodegradability. Numerous strains of pseudomonas, bacillus and Streptomyces have been seen to be related with the partial corruption of a wide range of petro plastics, including PE, PVC, PP, PU, PS and PVT. Based on the advances in the microbial metabolic pathways of depolymerization items, it will be interesting to apply synthetic biology to assemble microbial cell processing plants that could depolymerize plastic waste and the use of little depolymerization items to create synthetic compounds with high worth.

Table 1: List of microflora known for plastic degradation

MICROORGANISM	ENZYMES/ MEDIUM	PLASTIC	REFERENCE
BACTERIA			
Pseudomonas sp. E4	Alkane hydroxylase	LMWPE (Polyethylene)	Cell R et al 2012
P. putida AJ	Alkane hydroxylase	Vinyl Chloride (Polystyrene)	Danko S et al 2004
P. chlororaphis	Polyurethanase	Polyester (PUR)	Ruis GT et al 1999
P. aeruginosa	Esterase	Polyester (PUR)	Mukherjee K 2012
P. protegens BC212	Lipase	Polyester (PUR)	Hung C (2016)
P. fluorescen	Protease	Polyester (PUR)	Howard GT 1998
Pseudomonas sp.	Lipase	PET	Schrader (2005)
Pseudomonas sp. AKS2	Esterase	PES	Tribedi P, Sil AK (2014)
P. stutzeri	PEG dehydrogenase	Polyethylene glycol (PEG)	Obradors N 2000
P. vesicularis PD	Esterase	Polyvinyl alcohol (PVA)	Kawai, Hu X (2009)
R. arrizus	Lipase	PEA, PBS, and PCL	Tokiwa Y 2009
P. stutzeri	Serine hydrolase	PHA	Muhamad W 2015
Tremetesversicolor	Laccase	Nylon, PE	Mikihito Fujisawa 2001
Rhodococcusequi	Aryl acylamidase	PUR	Akutsu Y 1998
Brevibacillus borstelensis	Unknown	PE	Haded D et al 2005
Thermomonospora fusca	Unknown	PVC	Kleeberg C 1998
Schlegelella thermodepolymerans	Unknown	Poly(3-hydroxybutyrate-co3-mercaptopropionate)	Luftmann H (2015)
Streptomyces Scabies	suberinase	PET	Jabloune et al 2020
Bacillus	styrene monooxygenase	Styrene- monomer of PS	HO et al 2018
Serratia mercescens	Unknown	PS and Polycarbonate	Arefian et al 2020
Rhodococcus ruber	Laccase	PE	Santo et al 2013
Escheria coli	trypticase soy broth for 72 hrs	PU	Uscategui et al 2016
Pseudomonas aeruginosa	minimum salt media for 0.94 months	PS-PLA	Shimpi et al, 2012
Bacillus species strain 27	bushell haas media for 1.25 months	PP	Auta et al 2018

Bacillus species YP1	liquid carbon free media	PE	Yang et al 2014
Microbacterium paraoxydans	minimal broth media for 2 months	PE	Rajandas et al 2012
Bacillus cerus	films buried in soil for 7.5 months	PE	Nowak et al 2011
Rhodococcus sp. Strain 36	bushell haas media for 1.25 months	PP	Auta et al 2018
Arthrobacter sp. AF11	films buried in soil for 6 months	PU	Shah et al 2008
Micrococcus sp. AF10	films buried in soil for 6 months	PU	Shah et al 2008
Amycolaptosis species	manganese peroxidase	PLA , PE	Muhamad W 2015
Rhdoccocus ruber	NB medium for 10-14 days	PS	Mor and Sivan 2008
Curvularia sp.	sabouraud's broth for 13 days	PS	Motta et al 2009
Bacillus flexux	minimal media with glucose	PP	Arkatkar et al 2010
Bacillus cereus	mineral salt medium at 29 degree celcius	PP	Auta et al 2017
Pseudomonas citronellolis	MSM with glucose	PVC	Giacomucci et al 2019
Pseudomonas putida GO16	MSM medium with sodium terepthalate	PET	Kenny et al 2012
Idonella sakaiensis	NB Medium with pet at 30 degree	PET	Yoshida et al 2012
FUNGI		PHB	Aburas 2016
Aspergillus, Penicillium, Fusarium	unknown		
Acremonium recifei, *Paecilomyces lilacinus*	unknown	PHB/HB	Boyandin et al 2013
Penicillium oxalicum Strain DSYD05–1, *Penicillium oxalicum* SS2	unknown	PHB/HB	Li et al 2012 & Satti 2018
Pseudozyma japonica-Y7-09	unknown	PCL	Abdel - Motaal et al 2014
Clonostachys rosea and *Trichoderma* sp	unknown	PLA	Urbanek et al 2017
Trichoderma sp	unknown	PLA	Janczek et al 2018
Cladosporium and *Purpureocillium*	unknown	PBS	Penkhrue et al 2015
Aspergillus fumigatus 76T-3	unknown	PES & PBS	Jung et al 2018
Thermomyces laniginosa, *Aspergillus fumigatus*	unknown	PLA	Karamaglioglu 2014

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