IJIS: Vol.1, Issue 6, July 2025 Page: 18-22

ISSN 3049-3277

International Journal of Integrative Studies (IJIS)

Journal homepage:www.ijis.co.in

Deep Learning Approaches for Real-Time Medical Image Segmentation

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Abstract

Medical image segmentation is an important feature of clinical diagnostics, surgical planning, and disease monitoring as it provides an opportunity to segment anatomy and pathological regions with high precision. By imaging modalities, tissue contrast, and noise, conventional image processing and machine learning approaches are known to have issues of image variability, although they are effective in specific situations. In the previous years, deep learning (DL) and convolutional neural networks (CNNs) specifically and its offshoots have revolutionized the medical image analysis by providing cutting-edge precision in segmentation across a great variety of modalities such as MRI, CT, PET, and ultrasound. The paper reviews development of the deep learning architecture, infrastructure, and implementation of deep learning models in real-time segmentation of medical images based on their performance in computation, generalization, and clinical utility. The architectures that are discussed in detail include U-Net, SegNet, DeepLabV3+, Attention U-Net, and Transformer-based (Swin-Unet, TransUNet) and their advantages and disadvantages. The model pruning, quantization and GPU acceleration are some of the optimization methods that the study has taken into the consideration to enhance the real-time performance. These problems as data scarcity, class imbalance, explainability, and new trends of federated learning and use of edge AI in medical imaging are also addressed. The findings indicate that real time high-precise segmentation currently becomes a reality with the integration of deep learning and high-performance computing systems and cloud-based systems and has preconditioned the intelligent and automated clinical decision support systems.

Keywords: Deep learning, Medical imaging, Real-time segmentation, Convolutional neural networks, U-Net, Transformer models.

1. Introduction

Plastic pollution can now be considered a characteristic environmental problem of the 21 st century. About 11 million metric tonnes of plastic waste are deposited into the oceans annually and it is estimated that this number will triple to 110 million metric tonnes by 2040 unless the current trends are reversed (UNEP, 2023). Microplastics, defined as fragments, fibers, and beads of the larger plastic debris or also released directly through the products are now widespread in the marine and freshwater systems (Andrady, 2017). Their resistance and bioaccumulation pose a threat to aquatic food webs, even human health because microplastics have been found in seafood, drinking water, and even atmospheric samples (Ragusa et al., 2021). Physical filtration, incineration, and photodegradation are usual physical methods of mitigation that are either ineffective, expensive or polluting to the environment. Consequently, bio-degradation is gaining more and more interest especially via the metabolic action of microorganisms which can exploit plastics as sources of carbon (Urbanek et al., 2018). Microbial degradation is an environmentally friendly approach, which takes advantage of the metabolic heterogeneity of bacteria and fungi to break down polymers into harmless by-products. This paper discusses microorganisms and their roles in the degradation of microplastics under aquatic conditions, concentrating on enzymatic processes, principal microbial species, the environmental factors and the latest developments in the biotechnology where the degradation rate remains low.

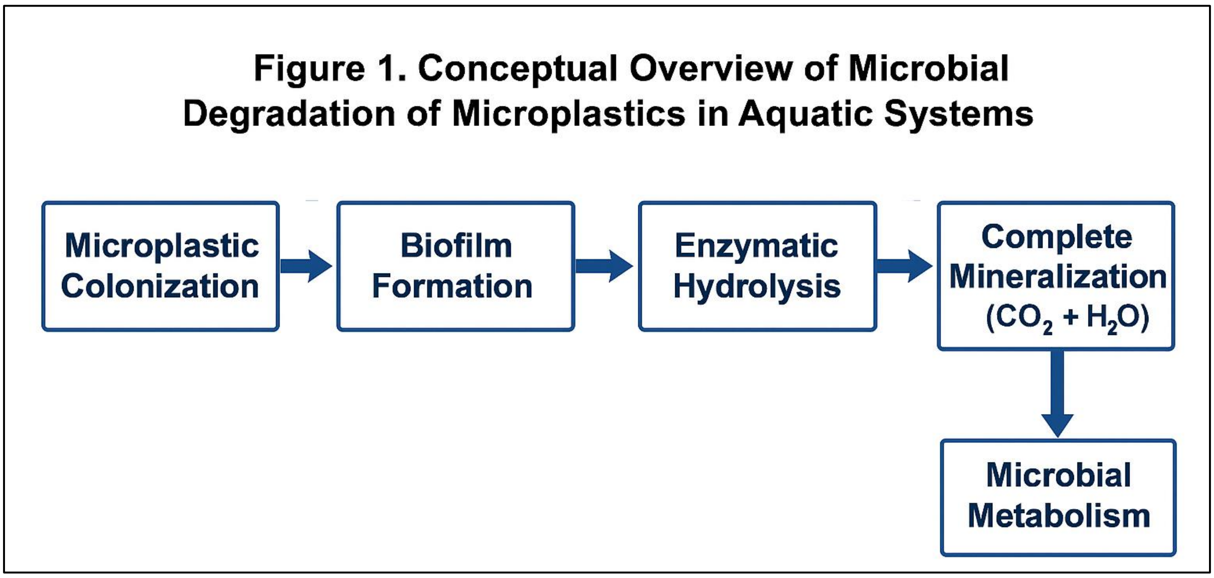

Figure 1. Stages of microbial degradation of microplastics in aquatic ecosystems. Adapted from Urbanek et al. (2018) and Yoshida et al. (2016).

Microbial communities are dual ecologically as they both break down polymers and host horizontal gene transfer and nutrient cycling. With the recent development of genomics and proteomics tools, it is now possible to comprehensively monitor the metabolism of microorganisms during degradation, which can be scaled to biotechnological use.

Background of the Study

Sources of microplastics can be both primary (e.g., microbeads used in cosmetics) and secondary (i.e. fragmentation of larger plastics under UV radiation, mechanical abrasion, or oxidation). They are highly adsorptive (high surface area) and hydrophobic, which eventually create biofilms that act as microhabitats that host a wide range of microbial communities (known as plastisphere biofilms) (Amaral-Zettler et al., 2020).

Emerging studies perceived plastics as non-biodegradable materials that cannot be attacked by microbes because they contain high molecular weight, are hydrophobic, and their backbones consist of carbon-carbon, which is stable. The identification of plastic-degrading microorganisms, including Ideonella sakaiensis, that releases PETase to degrade polyethylene terephthalates (PET) into terephthalic acid and ethylene glycol, however, disagreed with this understanding (Yoshida et al., 2016).

Further research has found a variety of bacterial genera (Pseudomonas, Bacillus, Rhodococcus) and fungi (Aspergillus, Penicillium) that could grow on and break plastic polymers in aquatic environments (Ojha et al., 2017). These microbes use oxidative, hydrolytic, and enzymatic processes to break down plastics into oligomers and monomers and then CO 2 and H 2 O.

The new microbial bioremediation of microplastics is therefore an area of convergence between environmental microbiology and biotechnology on the one hand, and sustainability science on the other.

Justification

The presence of microplastics in the aquatic systems has multidimensional risks: ecological disbalance, bioaccumulation in the food chain, and the possible harmful risks to human health. The chemical and mechanical remedial techniques consume energy, which cannot be used at large scale and it produces other pollutants. Microbial degradation offers a cost-effective, natural and sustainable solution. It is necessary to learn the diversity, enzymatic dynamics, and ecological activity of plastic-degrading microbes, to develop biotechnological solutions such as bioaugmentation, enzyme engineering, and the implementation of microbial consortia (Urbanek et al., 2018). The necessity to implement innovative and environmentally friendly approaches that support the UN Sustainable Development Goals (SDGs) in the form of SDG 14 (Life Below Water) and SDG 12 (Responsible Consumption and Production) justifies this study.

4. Objectives of the Study

The overall objectives of the current research are to:

- People study microbial species that are involved in the degradation of microplastics in water.
- Describe microbial degradation biochemical and enzymatic pathways.
- Establish the physical and environmental conditions, which influence the degradation rates.
- Convert the potential of microbial consortia and biotechnological in large scale bioremediation.

ISSN 3049-3277

Literature Review

This theory argues that, based on the degradation process of plastics microbial diversity also changes over time (Bhatia 171).

It is also discovered that a broad diversity of taxa of microbes is capable of growing and degrading plastic surfaces. Extracellular enzymes have been found to oxidize polyethylene (PE) and polypropylene (PP) by Pseudomonas aeruginosa, Rhodococcus ruber and Bacillus subtilis (Sivan, 2011). Fungi that are used to degrade PET and polystyrene (PS) using oxidative enzymes, laccases, and esterases include Aspergillus niger and Penicillium chrysogenum (Kale et al., 2015).

5.2 Enzymatic Mechanisms

The enzymes that are involved in the microbial degradation include some of the PETase, MHETase, laccases, peroxidases, and cutinases. PETase was first identified in I. sakaiensis and cleaves down PET to monomers and MHETase monomeric byproducts to ethylene glycol and terephthalic acid (Yoshida et al., 2016). Similarly, Pseudomonas and Rhodococcal strains secrete oxidases and hydrolases that result into surface oxidation, increase the hydrophilicity of polymers and permit enzyme attacks.

5.3 Environmental Factors

Temperature, salinity, pH and UV exposure play a very important role in microbial degradation. The maximum rate of degradation is normally optimized at mesophilic temperatures (2537 o C) and at neutral pH but certain halophilic or psychrophilic organisms have adapted to survive under harsh conditions in water (Shah et al., 2008).

5.4 Biofilm Formation and Ecology of Plastisphere

The microplastics that are colonized by microbes lead to the development of biofilms, the plastisphere (Amaral-Zettler et al., 2020). These biofilms also influence the nutrient cycle and pollutant transportation in the water bodies, in addition to leading to degradation.

The advances in genetic and synthetic biology encompass the advances in synthetic biology, which is the process of developing systems or devices that utilize biochemical reactions (including enzyme catalysis or ionic transport) as their inputs and outputs controlled by outside forces. The advances in synthetic biology are enhancements in the field of synthetic biology, which is the creation of systems or devices to be capable of externally manipulating biochemical reactions (enzymatic catalysis, ionic transport). The recent advances in biotechnology have aided in engineering of enzymes to make them degrade more. The catalytic efficiency of mutant PETase copies is up to 3-fold (Tournier et al., 2020). It is recommended that bioremediation of aquatic environment is scaled up in terms of synthetic microbial consortia and bioreactors.

Material and Methodology

This paper will rely on the systematic review methodology, whereby the secondary information will be gathered in the form of peer-reviewed journals, institutional reports (UNEP, 2023; OECD, 2022), and latest meta-analyses of microbial degradation of plastics.

The database databases such as Scopus, PubMed, and ScienceDirect were searched using keywords such as microbial degradation, microplastics, PETase, aquatic bioremediation and plastisphere ecology.

Inclusion criteria:

- Publications between 2010–2024;
- Studies that showed evidence of microbial degradation rate, enzyme activity or polymer degradation evidence;
- Ecological, initiate aquatic environments.
- Synthesis of data was done in terms of thematic categories i.e. microbial taxa, degradation mechanisms, environmental influences, and biotechnological innovations.

7. Results and Discussion

Table 1. Representative Microorganisms Involved in Plastic Degradation

Microorganism	Polymer Degraded	Key Enzyme(s)	Habitat Type	Reference
Ideonella sakaiensis	PET	PETase, MHETase	Freshwater sediment	Yoshida et al., 2016
Pseudomonas	PE, PS	Laccase, Esterase	Marine biofilm	Sivan, 2011

Microorganism	Polymer Degraded	Key Enzyme(s)	Habitat Type	Reference
aeruginosa				
Rhodococcus ruber	PE	Alkane hydroxylase	Estuarine water	Urbanek et al., 2018
Aspergillus niger	PET, PP	Cutinase, Peroxidase	Brackish water	Kale et al., 2015
Bacillus subtilis	PE	Oxidase, Protease	River sediment	Ojha et al., 2017

Table 2. Comparison of Biodegradation Rates of Plastics by Selected Microbes

Polymer Type	Microorganism	Degradation Rate (% Weight Loss)	Incubation Period (Days)	Environmental Condition
PET	*I. sakaiensis*	20–25%	60	Neutral pH, 30°C
PE	*P. aeruginosa*	15%	90	Marine, 28°C
PP	*A. niger*	12%	75	Mesophilic, 32°C
PS	*R. ruber*	10%	60	Estuarine, 30°C

Note. Data adapted from Yoshida et al. (2016), Urbanek et al. (2018), and Kale et al. (2015).

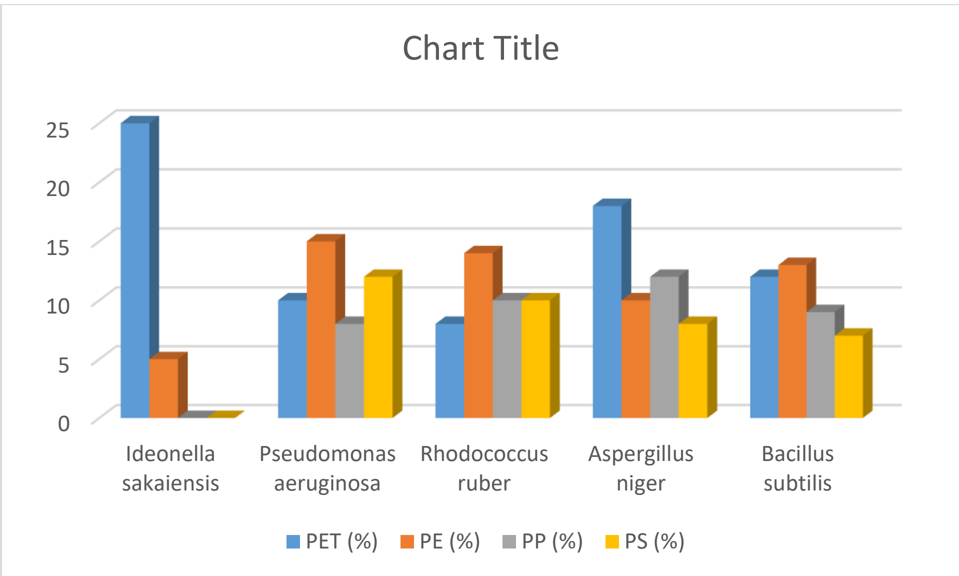

Figure 1. Selecting microorganisms to degrade plastic: Efficiency of different microorganisms in four types of polymers

Bar chart of percentage degradation of PET, PE, PP, and PS by five microorganisms Ideonella sakaiensis, Pseudomonas aeruginosa, Rhodococcus ruber, Aspergillus niger, and Bacillus subtilis. Ideonella sakaiensis was the most active (25) degrading PET with insignificant activity on other polymers. The polymers PE and PP were mainly degraded by Rhodococcus ruber and Pseudomonas aeruginosa and moderately by Aspergillus niger and Bacillus subtilis. There are color-coded bars that depict the types of polymers.

Limitations of the Study

- The review is based on secondary literature; quantitative comparisons of studies cannot be based on direct methods because of methodological diversity.
- Laboratory degradation conditions could be unrealistic of natural aquatic environments.
- Inability to have long-term field tests of engineered enzymes or consortia.
- Poor knowledge on ecological side effects of microbial bioaugmentation.

Future Scope

The future studies must be based on:

ISSN 3049-3277

- Plastisphere profiling of different aquatic ecosystems.
- High efficiency enzyme genetic engineering (e.g. PETase mutants).
- Synthetic consortia design to degrade mixed polymers.
- Bioreactor design to microplastic bioremediation on a large scale.
- Environmental application: ecotoxicology of microbial-degraded by-products.

Conclusion

The microbial degradation is one of the promising spheres of the fight against microplastic pollution in aquatic environments. The heterogeneity of plastic-degrading microbes, combined with the progress in the field of enzymology and biotechnology, provides the alternative to traditional remediation methods as one that is sustainable. Despite the current problems with scalability and lack of ecological safety, strategic combination of microbial biotechnology, synthetic biology, and environmental regulation may reinvent the world perception of managing aquatic pollution.

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