International Journal of Chemical and Biochemical Sciences
(ISSN 2226-9614)
Journal Home page: www.iscientific.org/Journal.html

Potential Microbes for Microplastic Biodegradation: Bibliometric Analysis using VOSviewer

Laras Finesha Melania, Aprilina Purbasari*

Master Study Program, Department of Chemical Engineering, Universitas Diponegoro, Semarang, Indonesia

Abstract

The current study aimed at assessing the significant impact of plastic waste on ecosystems has raised concerns regarding its detrimental effects. Microplastics are extensively spread and a significant contaminant in our environment. Microplastics are microscopic plastic particles (< 5mm) found in the environment which come from agrarian, businesses and home trash. Plastic particles are more durable because they include the plasticizers and chemicals or additives. Plastic pollutants are more resilient to degradation. Improper recycling and over use of plastic cause a considerable quantity of debris to accumulate in the natural landscape addressing danger to both humans and creatures. There is a strong urge to reduce microplastic pollution through various methods to prevent environmental hazards. Degradation through biological processes or biodegradation is one of the methods that can be applied depending on several factors such as chemical structures, functional groups, molecular weights, crystallinity, and additives. The several microbes that are used as agents to degrade molecular plastic have not been extensively studied. Sort out mandatorily for it to degrade due to microplastic problems. This review takes an advances towards different microbes to degrade different polymers by assembling data from Dimension, Scopus and VOS Viewers as analysis tools. This current study highlights the potentiality bacteria and fungi to breakdown plastic. To the current state of our study comprehension, this serve as the earliest article mapping trend in scope of potential microorganism capability to microplastic biodegradation waste with the highlight to aligning such endeavors with the commitment of sustainable development.

Keywords: Pollutant, Microplastic, Biodegradation, Microorganism

Full length article **Corresponding Author*, e-mail: lfinesha@gmail.com Doi # https://doi.org/10.62877/118-IJCBS-24-25-19-118

1. Introduction

Plastic waste is a globally common problem to ecosystem. Plastic that form microplastic are organic polymers come from non-renewable sources such as coal, natural gas, and crude oil [1]. Plastic who is very small size with <5mm diameter is referred as microplastic [2]. Microplastic that come from plastic waste widely distributed and become hazardous that cause threat in healthiness. In daily life, Microplastic could dispersed into water, soil, and sediments through daily use product, microplastic classified into two main type base on their source; primary and secondary microplastic. The first category is primary microplastic are generated from beauty products, dental products, healthcare supplies, and garment fibers, whereas secondary microplastic appears by the deformation of bigger plastic-based goods [3] [4]. Due to improper handling of the dump site, a significant quantity of microplastic circulates in the environment via several channels [4]. Based on [5] is about 8660 million metric ton of microplastic have been manufactured enormously, with 132 million metric tons of plastic was produced in Asia by 2021. Due to very small size it easily accumulates through the soil and water and cause change in physical properties and also chemical properties such as density, surfaces, and porosity. Both fauna that lives on such as pisces, nematodes snails and other invertebrate which are reported swollen microplastic [6] [7][8]. Categorized by the basic degradation which is biodegradable and non-biodegradable. The eco-friendly plastic form can completely degraded by microbes such as bacteria, fungi, and microalgae dissolved into carbon dioxide and water[9]. Despite the non-biodegradable microplastic refuse to degraded by microorganism. Numerous factor take effect in many ways to breakdown the plastic waste such as sun radiation and ocean waves[10]. Through the divergent methods; biological, thermal, photochemical and photocatalytic microplastic waste could be manageable [11] [12].

Biological degradable or most known as biodegradable is accomplish by some of type microorganisms that potentially to decompose organic elements in microplastic without reveal any threat for the environment [13]. The ambience have an important role for optimizing the microorganisms metabolic rate such as moisture, temperature, and also pH [14].

Thus far, a couple of microorganisms are studied to partly degrade microplastic. There are lacks of consciousness about biodegradation process for microplastic. However, there is nothing like an article review that employs of publications especially bibliometric analysis on biodegradation utilizing particular microbes to decompose microplastic under optimal circumstances. Few of them mostly focused on management of plastic waste, their impact on marine ecosystem, and tracers for monitoring by the country. The author highlights the gap by using tools VOS Viewers with future discussion for further research directions to gain its efficiency potential. The tools guide the authors more comprehensive integrated to multidisciplinary possible collaboration.

2. Materials and methods

The various data was performed for information on Dimension and Scopus on July, 3rd 2024. Those documents were redeemed from Dimension and Scopus for further processing. The following search scoped were :

- Dimension : ((“PLASTIC BIODEGRADATION” OR “POLYMER BIODEGRDATAION” OR “MICROPLASTIC BIODEGRADATION”) AND (“MICROBES” OR “MICROOGRANISMS” OR “BACTERIA” OR “FUNGI” OR “MICROALGAE”))
- Scopus : ((“PLASTIC BIODEGRDATAION” OR “MICROPLASTIC BIODEGRADATION”) AND (“MICROBES” OR “MICROOGRANISMS” OR “BACTERIA” OR “FUNGI” OR “MICROALGAE”))

Period time from 2017 to 2024 (n=550) and eliminated non-scientific article (n=548). A total 425 documents from Dimension. Associate with the Scopus core collection was scooped from 2019 to 2024 laid trends on biodegradation of plastic (n=325) and were found 81 documents were excluded as scientific articles. So thus, 244 articles more suitable. Related to those data, because the data from Dimension was higher than in Scopus, more advanced studies rely on Dimension database[15]. In this Bibliometric analysis, countries, authors, and keywords were analyzed using VOSviewer 1.16.19 [16]. Microorganisms such as bacteria, fungi, microalgae and other microbes are the agents to decomposed polymer. In this study, the type of polymer was not target, and the microorganisms that capable to degrade is the limitation.

3. Results and Discussions

In the extension of this case study, the terminations were collected and analyzed. These documents were retrivied from Dimensions and Scopus. The total 425 articles exported from Dimensions were published in 163 sources by 2243 authors. The number of collaboration was 13. The documents per Author were 5. The value of the collaboration index scored with average citation was 2.6 signifies high research collaboration[17].

3.1 Major Data Information

The main data focused on the microorganism role at biodegradation of plastic research are laid in Table 1. Total articles were 425 taken from Dimension.

3.2 Analysis Annual Trend

The number of published research documents through specific field are valuable for the broadening production trend[18]. As shown in Figure 1. It shown the publication in general had a growing trend over the years from both databases. The annual research increase in publication started from 2015 to 2020 the data was grown stable, but when 2020 to 2023 was grow extreme doubling each year. These consist of the year of publication and open paid access journal [17]. Previous publication is had been estimated to receive more citations than the recent releases. Although, publication in open access journals are simply accessible via various research search engines causing commonly cited compare to papers in paid access. Citation are expected to desirable by the quality of the research, for some cases it is not likely. The relationship among the quality and citation is an endless debate in scientometric [19]. Those number be accordance with statement global pandemic issues that impacted at amount of plastic waste [20] that become a concerned to support biodegradation processed [21]. The decreasing happened in 2023 to 2024 the data were collected this amount will increase due the developmental scope by the end of the year. Have a butcher’s at study in biotechnology advanced through the year specially at microbe potential had grew rapidly [22]. Thus, should become an opportunity to investigate the processes. Figure 2 represents the cooperation between countries all over the world through the years. From total 64 countries the most up to date country was recorded for the most up-to-date are China (n=178) and India (n=69). Anyhow, China known as the largest polymer-based material industry in global scale [23], [24] due the responsibility China take an effort to do research with plastic as their concern.

3.3 Analysis Authorship, Journal and Institution

The number of the publication in related field can reproach the research’s scope[25]. Currently, most authors in related fields biodegradation-microplastic are from China went to Tamer Elsamahy with 6 documents, Cited by 586. Though there are 10 most relevant authors shown in Table 2. For the bibliographic coupling of authors, it determine relation between documents based on the number references matched by the names [26]. The method establishes the possibility from the total documents had comparable subject and constructs a map that contains authors, institution and sources to reveal the involvement connection in biodegradation-polymer research. analysis authors, journal and relevant institution was achieved using the complete counting method with VOSviewer software. For bibliographic coupling, the requisite quantity document of author was three and 63 authors to meet the criteria. It shown on Figure 3, The 63 authors were grouped into 7 cluster in VOSviewer array into strength link. The author with the most connected consists of 6 documents with 586 citations. For the bibliographic coupling analysis of institution as shown in Figure 4, the minimum number of documents of an organization was 5. Thus, from 902 institution creates 31 meet thresholds. The 31 institutions were classified into 4 clusters. The foremost influential institution in plastic-biodegradation research between 2017 to 2024 was University of Chinese Academy of Sciences with 16 documents and already cited by 412 other documents.

Table 1: Major Data Information from 2017 to 2024

Description	Dimension	Scopus
Timespan	2017:2024	2017:2024
Documents	550	325
Articles	425	244
Authors	2243	243
Sources	163	143
Number of Collaboration	13	6
Documents per Author	5	2
Average Citations	2.6	3.1
Keywords (ID)	-	3.4

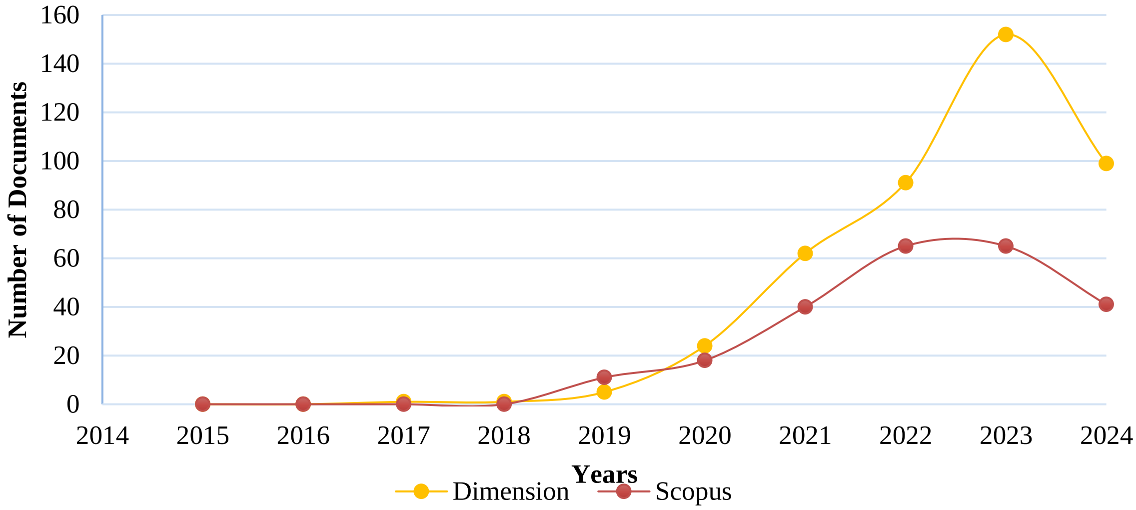

Figure 1: Analysis of Publication Years

Table 2: Rank of The Most Relevant Author

Rank	Author	Documents	Citation	Country
1	Tamer Elsamahy	6	586	China
2	Jianzhong Sun	6	586	China
3	Alok Prasad Das	7	125	India
4	Xiuna Ren	5	135	China
5	Daochen Zhu	3	556	China
6	Rania Altohamy	3	219	India
7	Abhijit Dey	3	108	India
8	Satarupa Dey	3	108	India
9	Yalan, Chen	6	73	China
10	Bo Jiang	3	76	China

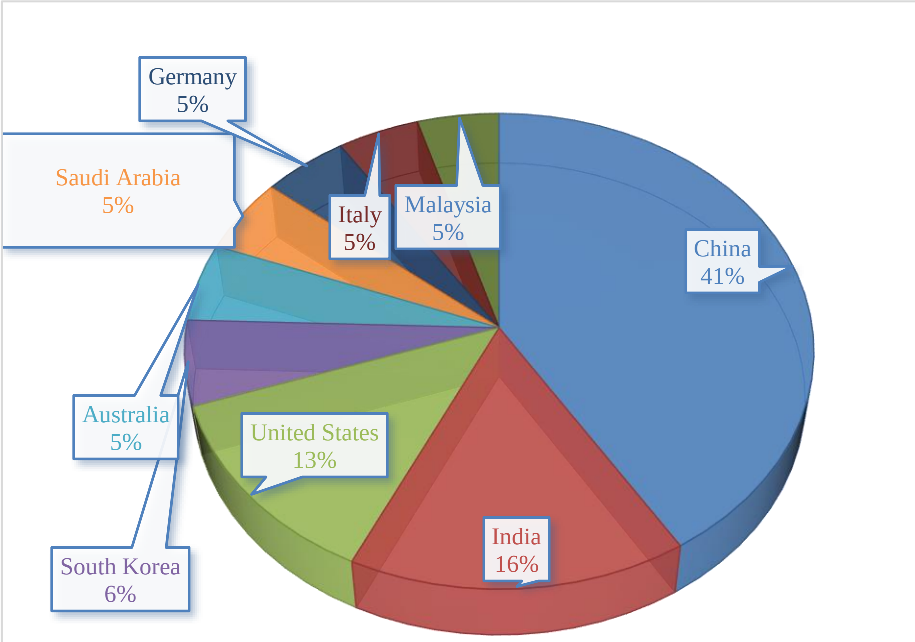

Figure 2: Countries from The Most

Update Research from 2017 to 2024

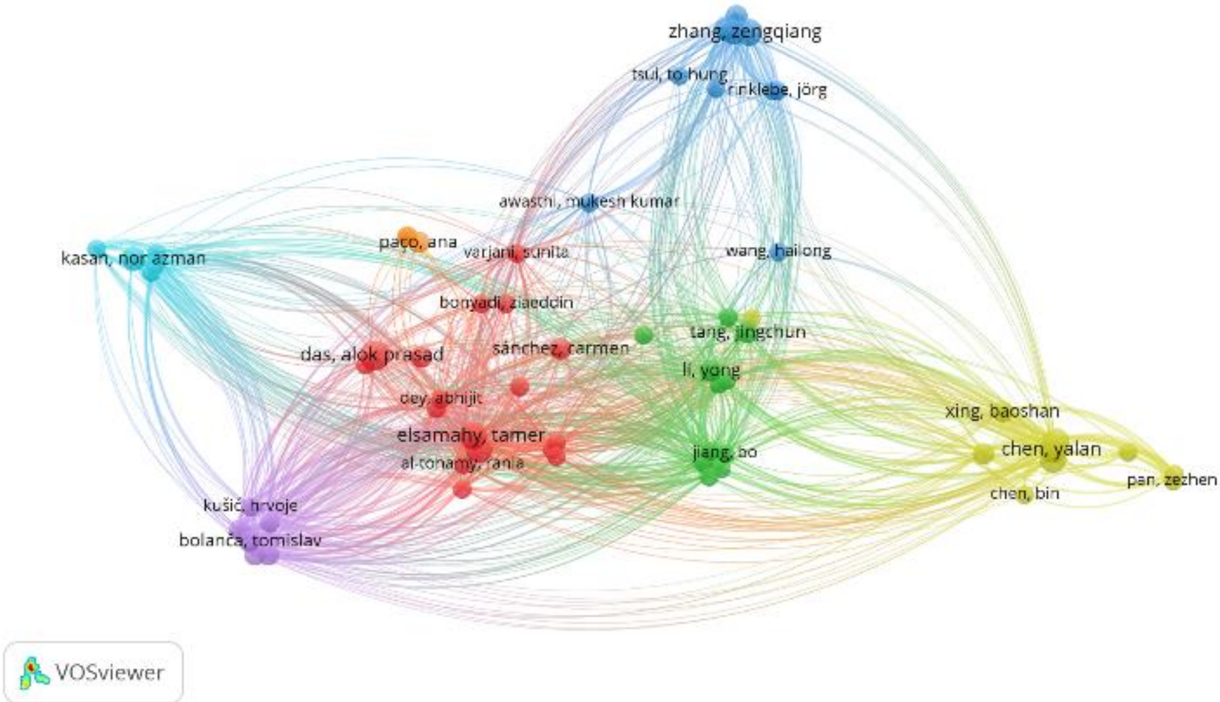

Figure 3: Bibliographic Coupling for Authors

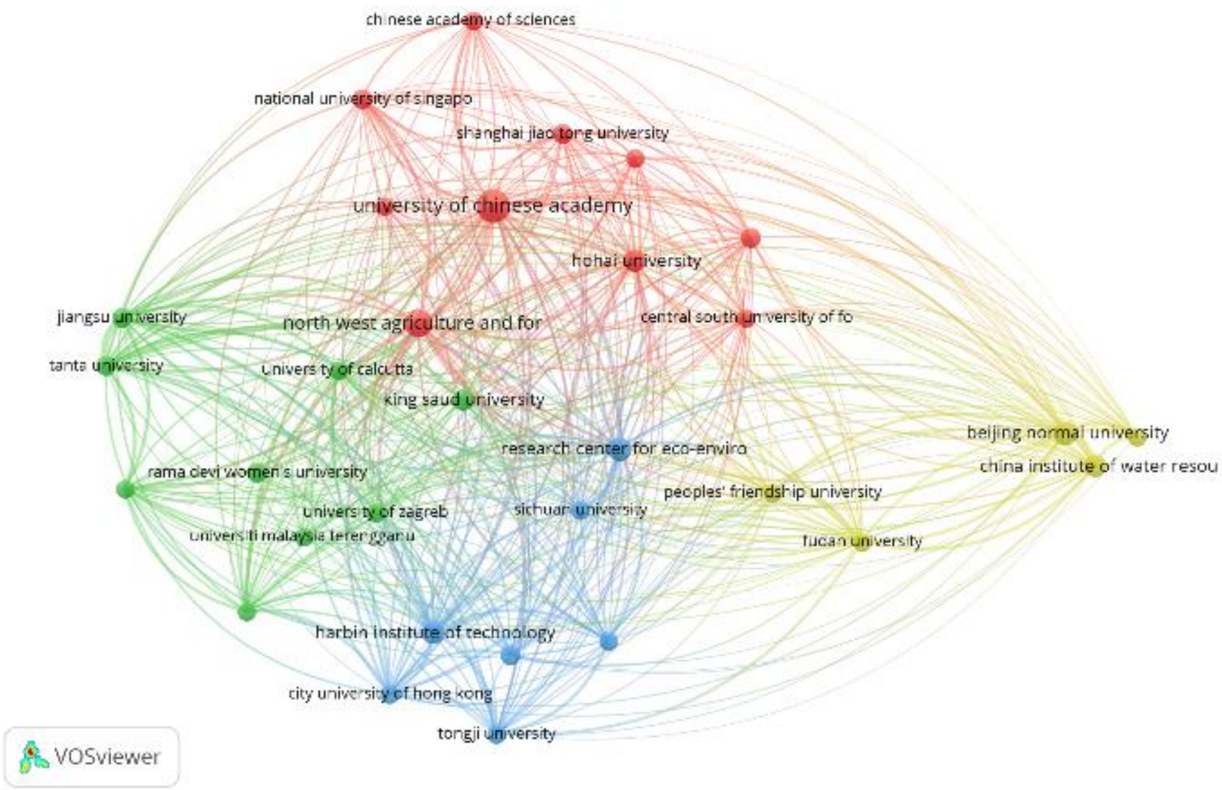

Figure 4: Bibliographic Coupling for Relevant Institution

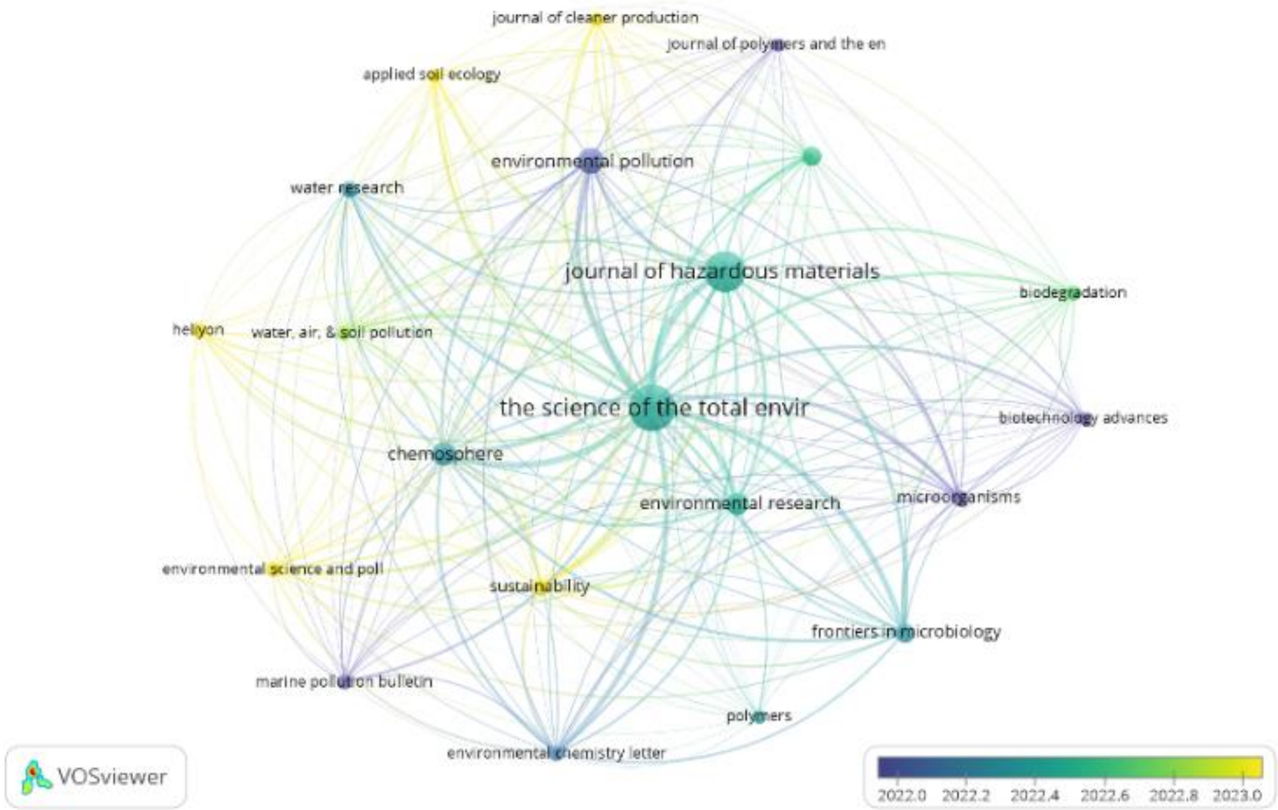

Figure 5: Bibliographic Coupling of Relevant Journal

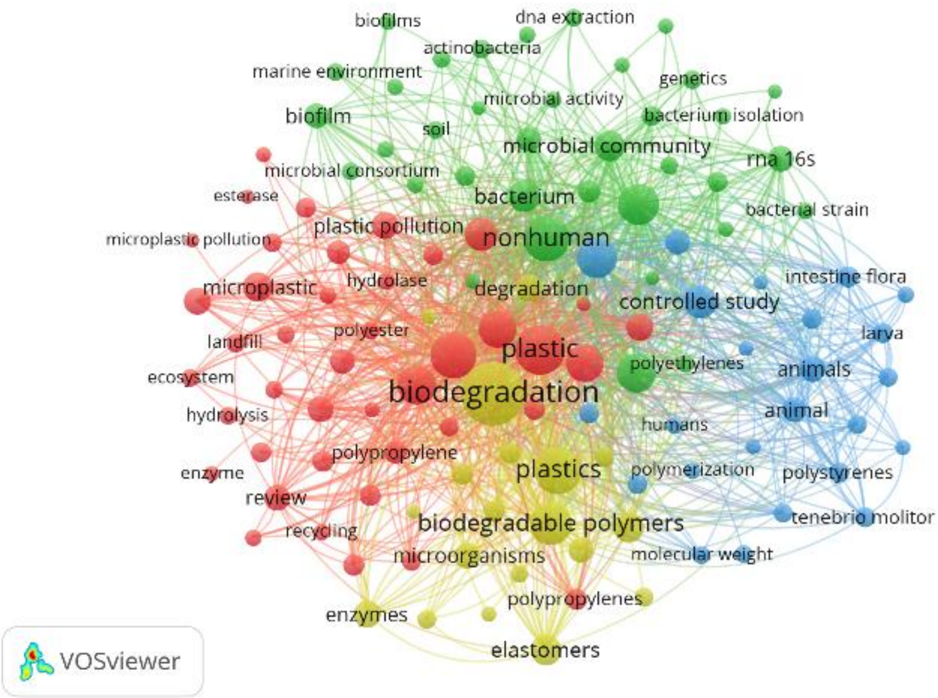

Figure 6: Analysis Co-Occurrence of Keywords

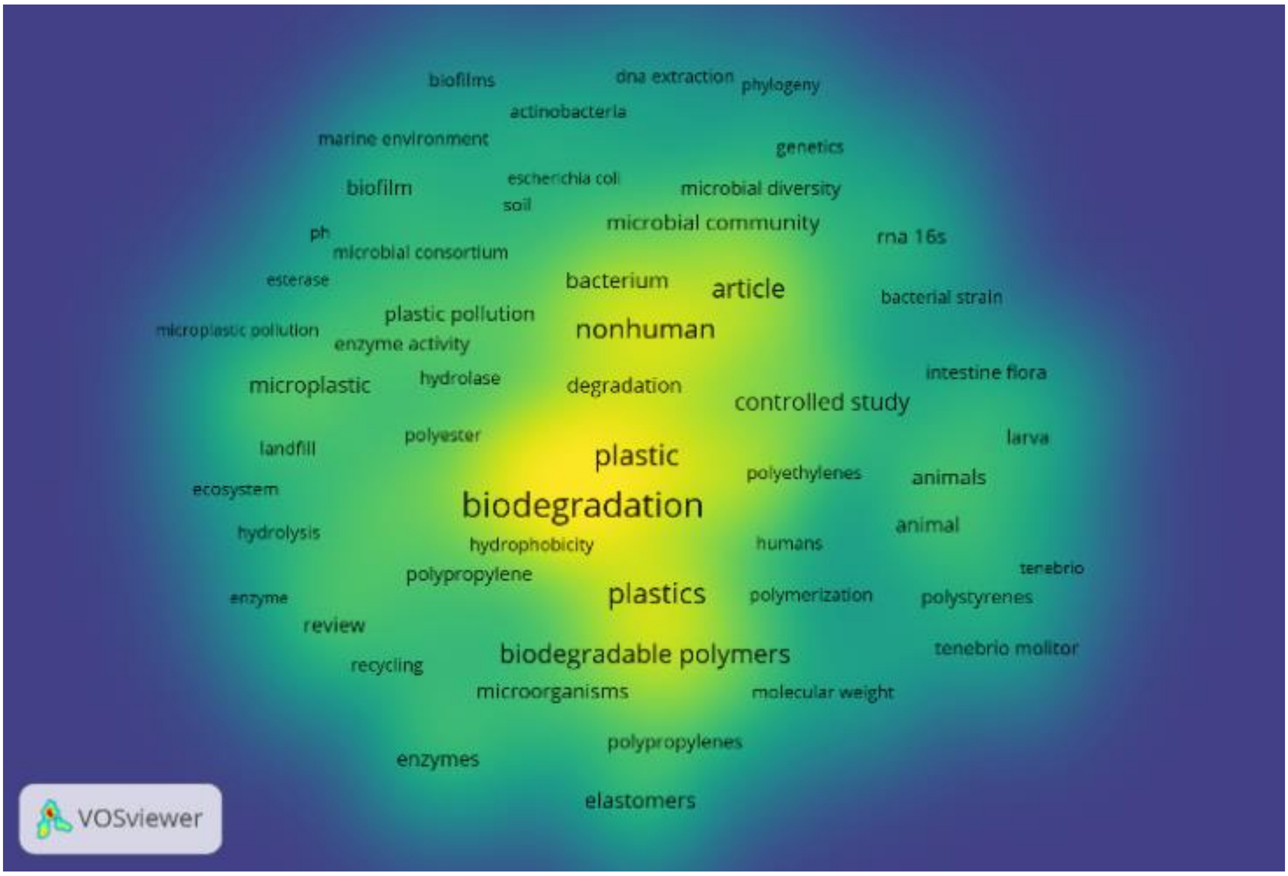

Figure 7: Visual Map Density Overlay of Keywords

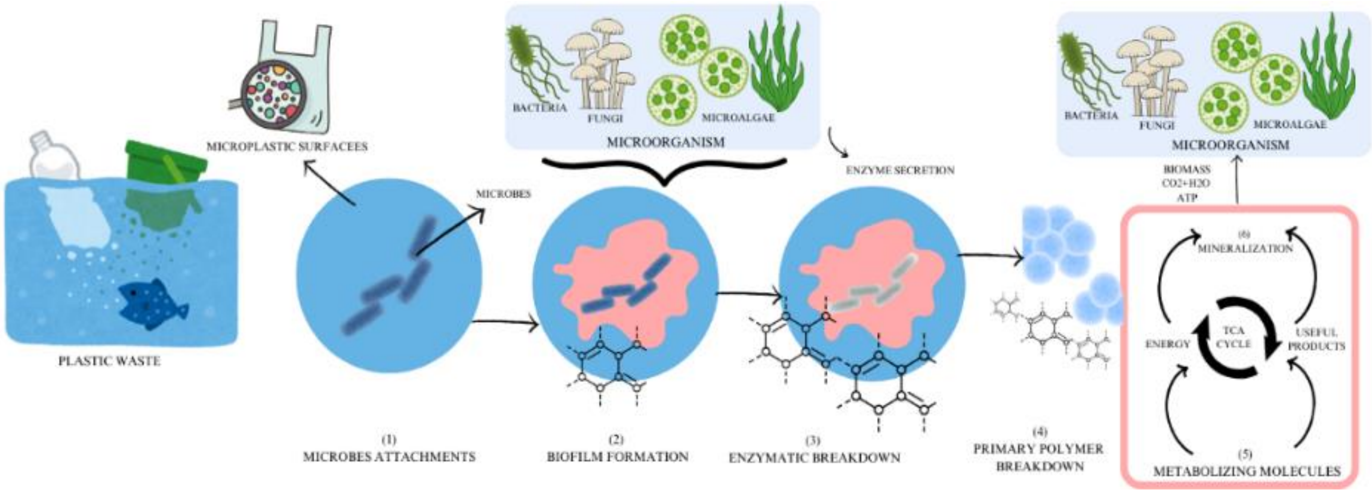

Figure 8: Mechanism for Biodegradation of Microplastic

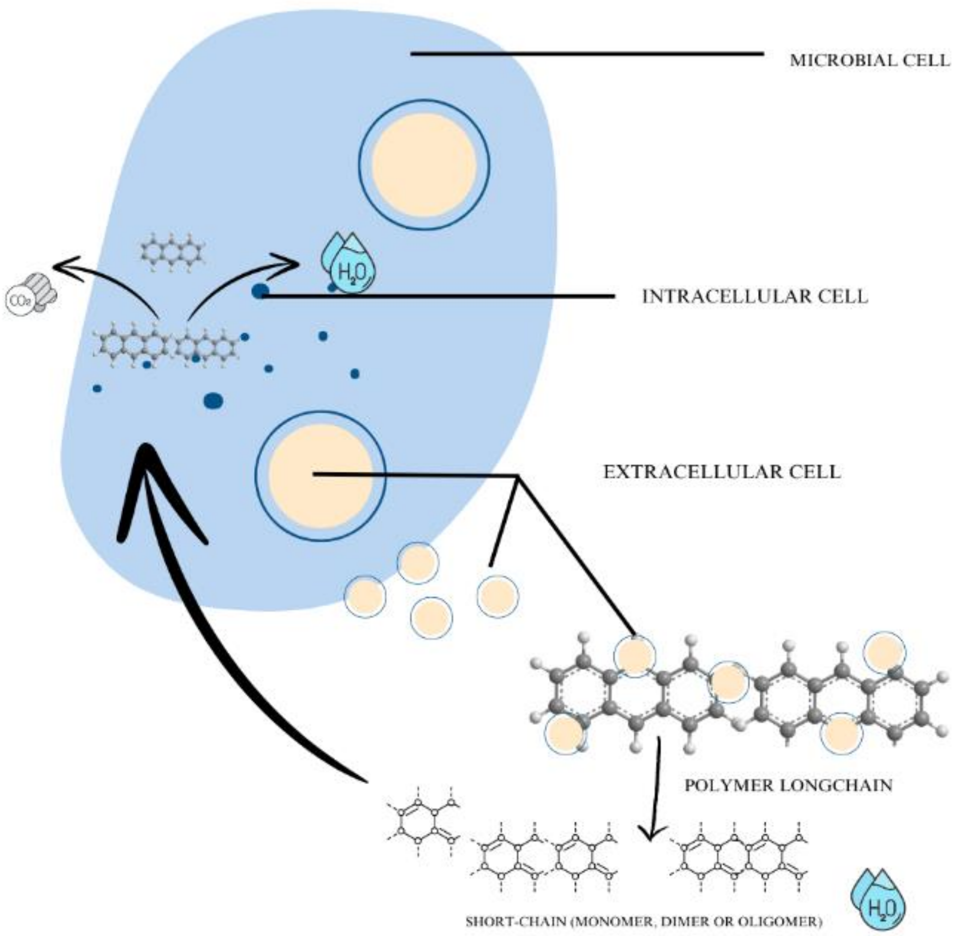

Figure 9: Secreted Enzymes by Microorganisms

Table 3: Potential Microbes in Current Study

Taxon	Isolate	Polymer	Enzyme	Time	Percentage of degradation	Ref.
Bacteria	*Lysinibacillus sp.* *Salinibacterium sp.*	PE		6mo	19%	[58]
	Bacillus pumilus	PE PP PS		40d	1.8-7.4%	[59]
	Bacillus cereus *Sporosarcina globispora*	PP		40d	12% 11%	[60]
	Bacillus sp. *Pseudomonas sp.*	PLA		40d		[61]
	Bacillus thuringiensis *Bacillus licheniformis*	PP PLA		15d	12% 10%	[62]
	Aneurinbacillus sp *Brevibacillus sp.*	HDPE LDPE PP		140d	47% 58% 56%	[63]
	Bacillus sp. *Paenibacillus sp.*	PP		60	14.7%	[64]
	Pseudomonas sp. *Rhodococcus sp.*	PP		40d	17.3% 7.3%	[65]
	Alcanivorax	LDPE		34d	0.9%	[66]
Fungi	*Zallerion Maritimum*	PE		28d		[67]
	Aspergillus tubingensis	PU				[68]
	Monascus sp.	PU	Prolase Esterase Lipase	14d		[69]
	Penicillium sp..	HDPE LDPE		60d		[70]
	Aspergillus Oryzae	LDPE PET		4mo 4d	5.53% 26%	[47] [71]
	Trichoderma viride *Aspergillus nomius*	LDPE		45d	58% 40%	[72]
	Aspergillus terreus *Aspergillus sydowii*	PE		60d	8.14%	[73]
	Chaetomium globosum	PVC		28d	45%	[74]
	Yarrowia lipolytica	PCL	Lipase Cutinase	6d		[75]
	Aspergillus fumigatus *Mycothermus termophilia*	PHA			22-31%	[76]
	Trichoderma hamatum	PVC		110d	33.2%	[77]
Algae	*Scenedesmus abundans*	PS PLA		6d	84%	[57]
	Scenedesmus sp. *Tertraselmis sp.* *Gloeocapsa sp.*	PS PMMA		21d		[56]

The majority research studies already used bibliometric to determine the influential institution by the authors in one particular area of interest [27], [28]. The allocation of this scope in peculiar topics are greatest described in journals with subject categories in bibliometric analysis [29]. As shown Figure 5, A total of 163 journals the 425 articles analyzed. The most relevant journal on this scope is The Science of Total Environment with 51 documents and cited by 2367. Then followed by Journal of Hazardous Material with 40 documents and cited by 1310. The analysis of relevant journal proofed that the studies in this scope had heterogeneous topic but point up the environmental issues. Plastics are not only critical issues but also threatened to human, soil, water, and the food chain [1], [6], [30]. Studies on the interaction between microplastic, microorganisms and human well-being may be likely improvement in biodegradation process.

3.4 Analysis Keywords

The trend of topics by year is shown in **Figure 6**, Keywords are selected based on data from Scopus. Co-occurrence analysis could be applied for discover current topics and trends for monitoring also tracking progress in scientific research and initiatives [31], [32]. Keywords are terms with significant meaning in communicating the essential topic of a work and draw attention to the main research directions in the field of study [33]. By using the full counting method, from the total 2895 keywords through minimum of occurrence of a keyword are 10, only 121 keywords meet the threshold and allocated into 4 cluster. The keywords indicators seem had a huge size, indicate the frequency occurrences. The amount of distance accross two keywords that connected through the link makes an uneven estimate of the relationship between the keywords. Every single cluster represented with different certain color to proclaim the connection between the keywords through the links [34]. Following this data, the most-mentioned keywords is "Biodegradation" seems the common occurrence density of keywords had strongest light yellow represent frequently cited keywords. From Figure 7, those keyword are evidences of the research scope over a decades between Scopus and other various researcher search engine to discover an advance field of biodegradation-plastic [22], [30], [35].

3.5 Analysis Degradation Mechanisms

Microplastic are polymeric substances that alrady existed in the environment for long time and hardly to degrade [36]. In recent years, build upon Co-occurance keywords from the data Scopus showed different types of microorganisms involved in the biodegradation process within enzymatic reaction. The aspect of the biological degradation of microplastic associated with degradation mechanism like its shown in Figure 8.

Microplastic biodegradation involves the breakdown of plastic particles by microorganisms through 6 simplified mechanisms. First, "Initial attachment" when the microbes attach to the surface of microplastic particles then facilitated by biofilms formed by microbial communities. Then, "Biofilm Formation" when microorganism produce extracellular polymeric substances (EPS) to form biofilm, providing environment for microbial communities to live. Microplastic is capable of providing a habitat that supports various specific microbial population, such as microplastic-degrading bacteria, who can affect the ecological function of the ecosystem and play a part in microplastic biodegradation. [37]. Next, "Enzymatic Breakdown" while microorganism secrete enzyme such as hydrolase, esterase, etc. that breakdown the complex polymer chains of plastics into smaller molecules. Afterwards, "Primary Degradation" where the plastic loses its structural integrity through enzymes degrade the long polymer chains of polymer into oligomers, dimers, and monomers. Thereafter, "Metabolizing Molecules" during primary degradation microorganism metabolize into smaller molecules that taken up by microbial cells and used as a carbon and energy sources. Lastly, "Mineralization" where the end products are carbon dioxide, water, biomass, and various organic compounds[14], [38].

Future studies also evaluate the interjection in decomposed polymers. Thus, had identified enzymes capability to degrading plastics with diverse level. The enzyme could be grouped into intercellular and extracellular depolymerases [13]. The enzyme that capable to catalyzing the hydrolysis of ester bonds in polyester (intercellular) are esterases and lipases [39]. The extracellular enzyme that capable to decompose complex polymer into short chains which are oligomers, dimers or monomers and the absorbed by microorganisms as carbon sources [40], [41]. The enzymes were secreted from microorganism as the key to degradation process that responsible to decompose polymer into methane, carbon dioxide, and water [42]. So, the intercellular and extracellular secreted by microorganism break the molecules and turn them into smaller molecules as shown in Figure 9.

3.6 Analysis Microorganisms

Currently, various organisms and enzymes have the potential of degrading plastic and have been published, while a degradation mechanism has been established[35]. The forthcoming research should involve the genomics role and metabolic method to make treasure trove field on microplastic biodegradation by fungi, bacteria, and enzymes. The fine points on list potential candidate natural microorganisms shown at Table 3.

The fungi have been used in various environmental intervention, and the data suggests that certain fungi are suitable target for plastic breakdown. Take a look at its structural units, mycelia, have the ability to penetrate the plastic surface, stretch and diffuse into the substrate to acquire nutrients, facilitating fungi to firmly adhere to the plastic surface[30]. The extracellular enzyme from fungal cells such as peroxidases, laccases, cutinases, lipases, and proteases extracted for did an important role to process depolymerizing polymeric materials into smaller molecules [43], [44]. Another studies, discover capability fungi to secreted hydrophobins (surfactant) which as the most active surface proteins do self-assemble to form amphiphilic protein membranes that enhance hydrophilicity of the polymer surface and support fungal colonization on the polymer surfaces [45], [46]. As a comparison, [47] studied 26 species of fungi (mostly *Penicillium spp*. And *Aspergillus spp.*) were more efficient in LDPE biodegradation based on weight reduction than bacteria in the soil colonies. At the end of the day, through these benefits are applicable and promising in the plastic biodegradation fields. The bacterial candidates majority capable of biodegrading plastic which have been identified as potential degradation agents [48]. Bacteria depolymerize plastic into low molecular weight compounds that can be utilized by cells through forming biofilms and series of enzymatic reactions [44]. Between all the bacteria, the most mentioned were *Pseudomonas spp*., *Bacillus spp.*, and *Stn reptomyces spp.*, effectively degrading plastic since its versatile, and adaptable[49], [50]. Also, it has been reported few bacteria consortium discovered on arthropods guts degraded vary polymer [44], [51], [52]. Moreover, several studies were implemented under the artificial laboratory system where the impact of environmental factor such as pH, temperature, substrate concentration, and atypical surfactant [53], [54]. Nevertheless, it also has some limitations as the most of the type of polymer are distinctly lasting and degrade uneasily. Mostly, it takes prolonged and might visible between 8-12 weeks.The ocean where plastic pollution heavy-handed while algae are inhibiting, thus are suitable match to aid the urgency. Even if the specific degradation mechanism particularly elusive, the key elements are the capability algae to adhere on polymer while extracellular polymeric substances (EPS) secreted to strengthen adsorption and help to form hetero-aggregation for automatically sediment [55], [56]. In this case, microplastic which PS (Polystyrene) in 2μm diameter up to 84% in 9h by the microalgae *Scendesmus abundans*[57]. Set side by side current research in fungi and bacteria, the ability of algae between biodegradation and heterogeneous aggregation grant them to potentially remove microplastic from aqueous environment.

4. Conclusions

Large amount of plastic waste accumulating in the environment as microplastic that causing risk to human and ecosystem. There is an urge to develop technologies to decompose the microplastic, one possible way is biodegradation microplastic helped by microorganism.

In summary, the study demonstrates the remarkable potential of microbe for degradation especially microplastic. Different strains of microorganisms involved in the biodegradation process. Showcasing the mechanism of biodegradation absolutely must be under optimal condition with different factors. The degradation process was helped by enzymes reaction that secreted from microorganisms. This finding suggests promising application in environmental remediation, particularly in addressing pollution from environmental and human well-being. While the current results are promising, further research is needed to assess the feasibility of large scale application and long-term effects. So far, from the total article have been published encouraging the unambiguous mechanisms for biodegradation process of microplastic is an analytical experimental gap that should be run through. The present review, highlight the microorganism capability to degrade polymer focused on microplastic associated with enzymatic mechanism. The continued exploration of microbial solutions could revolutionize waste management and contribute to a more sustainable future.

References

[1] V. Hidalgo-Ruz, L. Gutow, R. C. Thompson, and M. Thiel. (2012). Microplastics in the marine environment: A review of the methods used for identification and quantification," Environmental Science Technology. 46. 6. : 3060–3075.

[2] N. Mourgkogiannis, I. K. Kalavrouziotis, and H. K. Karapanagioti. (2018). Questionnaire-based survey to managers of 101 wastewater treatment plants in Greece confirms their potential as plastic marine litter sources" Marine Pollution Bulletin. 133. 6. : 822–827.

[3] A. H. Hamidian, E. J. Ozumchelouei, F. Feizi, C. Wu, Y. Zhang, and M. Yang. (2021). A review on the characteristics of microplastics in wastewater treatment plants: A source for toxic chemicals. Journal Cleaner Production 295. : 126480.

[4] K. Zhang et al. (2021). Understanding plastic degradation and microplastic formation in the environment: A review. Environmental Pollution. 274.

[5] P. R. Bhoi. (2021). An overview of non-biodegradable bioplastics. Journal of Cleaner Production. 294.

[6] A. Abel, D. S. Machado, C. W. Lau, W. Kloas, and J. Bergmann. (2019). Microplastics Can Change Soil Properties and Affect Plant Performance. Environmental and Science Technology. 53. : 6044−6052.

[7] D. He, Y. Luo, S. Lu, M. Liu, Y. Song, and L. Lei. (2018). Trends in Analytical Chemistry Microplastics in soils : Analytical methods , pollution characteristics and ecological risks. Trends Analysis Chemistry 109. : 163–172.

[8] F. Feizi, R. Akhbarizadeh, and A. H. Hamidian. (2024). Microplastics in urban water systems, Tehran Metropolitan, Iran. Environmental Monitot Assessment. 196. 7.

[9] X. F. Wei, M. Bohlén, C. Lindblad, M. Hedenqvist, and A. Hakonen. (2021). Microplastics generated from a biodegradable plastic in freshwater and seawater. Water Research. 198. : 117123.

[10] Y. Du, X. Liu, X. Dong, and Z. Yin. (2022). A review on marine plastisphere: biodiversity, formation, and role in degradation. Computational Structure Biotechnology Journal. 20. : 975–988.

[11] Q. Y. Lee and H. Li. (2021). Photocatalytic degradation of plastic waste: A mini review. Micromachines. 12. 8.

[12] M. Golmohammadi et al. (2022). Photocatalytic nanocomposite membranes for environmental remediation. Nanotechnology. 33. 46. : 465701.

[13] J. Yuan, J. Ma, Y. Sun, T. Zhou, Y. Zhao, and F. Yu. (2020). Microbial degradation and other environmental aspects of microplastics/plastics. Science Total Environment. 715. : 136968.

[14] Z. Lin et al. (2022) Current progress on plastic/microplastic degradation: Fact influences and mechanism. Environmental Pollution. 304. 3.

[15] C. Herzog, D. Hook, and S. Konkiel. (2020). Dimensions: Bringing down barriers between scientometricians and data. Quantitative Science

Study. 1. 1. : 387–395.

[16] U. A. Bukar, M. S. Sayeed, S. F. A. Razak, S. Yogarayan, O. A. Amodu, and R. A. R. Mahmood. (2023). A method for analyzing text using VOSviewer. MethodsX. 11. 5. : 102339.

[17] D. W. Aksnes, L. Langfeldt, and P. Wouters. (2019). Citations, Citation Indicators, and Research Quality: An Overview of Basic Concepts and Theories. SAGE Open. 9. 1.

[18] M. Li, N. Gao, S. Wang, Y. Guo, and Z. Liu. (2023). A global bibliometric and visualized analysis of the status and trends of gastroparesis research. Europe Journal Medical Research. 28. 1.

[19] L. Leydesdorff, L. Bornmann, J. A. Comins, and S. Milojevic. (2016). Citations: Indicators of Quality? The Impact Fallacy. 1. 8. : 1–15.

[20] L. Madej-Kiełbik, J. Jóźwik-Pruska, R. Dziuba, K. Gzyra-Jagieła, and N. Tarzyńska. (2014). The Impact of the COVID-19 Pandemic on the Amount of Plastic Waste and Alternative Materials in the Context of the Circular Economy. Sustainable. 16. 4.

[21] S. Mishra, D. Dash, and A. P. Das. (2024). Aquatic Microbial Diversity on Plastisphere: Colonization and Potential Role in Microplastic Biodegradation. Geomicrobiology Journal. 41. 4. : 312–323.

[22] Y. Cao et al. (2024) Progress and Prospects of Microplastic Biodegradation Processes and Mechanisms : A Bibliometric Analysis. Toxics. 12. 463.

[23] X. Luan et al. Dynamic material flow analysis of plastics in China from 1950 to 2050. Journal Cleaner Production. 327. 6. : 129492.

[24] X. Jiang et al. (2020) Assessment of Plastic Stocks and Flows in China: 1978-2017. Resource Conservative Recycle. 161. 6.

[25] S. B. Borrelle et al. (2020) Mitigate Plastic Pollution. Science. 1518. no. 9. : 1515–1518.

[26] B. Jarneving. (2017). Bibliographic coupling and its application to research-front and other core documents. Journal Informetrics. 1. 4. : 287–307.

[27] J. Matsimbe, M. Dinka, D. Olukanni, and I. Musonda. (2022). A Bibliometric Analysis of Research Trends in Geopolymer. Materials (Basel). 15. 19. : 0–16.

[28] C. Y. Kwon. (2023). Research Trends of Pharmacopuncture: a bibliometric analysis using VOSviewer (2007-2023). Journal Pharmacopuncture. 26. 3. : 227–237.

[29] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. Marc. (2021). How to conduct a bibliometric analysis : An overview and guidelines Journal Bussiness Resolution. 133. 5. : 285–296.

[30] C. Sánchez. (2020). Fungal potential for the degradation of petroleum-based polymers: An overview of macro- and microplastics biodegradation. Biotechnology Advance. 40. : 107501.

[31] D. Xu et al. (2022). A review on the remediation of microplastics using constructed wetlands: Bibliometric, co-occurrence, current trends, and future directions. Chemosphere. 303. P1. : 134990.

[32] A. Barberán, S. T. Bates, E. O. Casamayor, and N. Fierer. (2022). Using network analysis to explore co-occurrence patterns in soil microbial communities. ISME Journal. 6. 2. : 343–351.

[33] F. Qin et al. (2020). Bibliometric profile of global microplastics research from 2004 to 2019. International Journal Environmental Research Public Health. 17. 16. : 1–15.

[34] C. Jia and H. Mustafa. (2022). A Bibliometric Analysis and Review of Nudge Research Using VOSviewer sciences. Behavioral Science. 13. (1). : 19.

[35] Z. Wu, W. Shi, T. G. Valencak, Y. Zhang, G. Liu, and D. Ren. (2023). Biodegradation of conventional plastics: Candidate organisms and potential mechanisms. Science Total Environment. 885. 4. : 163908.

[36] M. C. Krueger, H. Harms, and D. Schlosser. (2015). Prospects for microbiological solutions to environmental pollution with plastics. Applied Microbiology and Biotechnology. 99. 21. : 8857–8874.

[37] Y. Huang, Y. Zhao, J. Wang, M. Zhang, W. Jia, and X. Qin. (2019). LDPE microplastic films alter microbial community composition and enzymatic activities in soil. Environmental Pollution. 254. : 112983.

[38] A.-U.-R. Bacha, I. Nabi, M. Zaheer, W. Jin, and L. Yang. (2023). Biodegradation of macro- and micro-plastics in environment: A review on mechanism, toxicity, and future perspectives. Science Total Environment. 858. : 160108.

[39] Roohi et al. (2017). Microbial enzymatic degradation of biodegradable plastics. Current Pharmaceutic Biotechnology. 18. 5. : 429 – 440.

[40] J. D. Gu. (2023). Microbiological deterioration and degradation of synthetic polymeric materials: Recent research advances. International Biodeteriorientation Biodegradation. 52. 2. : 69–91.

[41] J. Peixoto, L. P. Silva, and R. H. Krüger. (2017). Brazilian Cerrado soil reveals an untapped microbial potential for unpretreated polyethylene biodegradation. Journal Hazardous Material. 324. : 634–644.

[42] S. Sharma, S. Basu, N. P. Shetti, M. N. Nadagouda, and T. M. Aminabhavi. (2020). Microplastics in the environment: Occurrence, perils, and eradication. Chemical Engineer Journal. 408. 10.

[43] M. Srikanth, T. S. R. S. Sandeep, K. Sucharitha, and S. Godi. (2022). Biodegradation of plastic polymers by fungi: brief review. Bioresource Bioprocess. 9. 1.

[44] S. S. Ali et al. (2021). Plastic wastes biodegradation: Mechanisms, challenges and future prospects. Science Total Environmental. 780.

[45] P. Cicatiello, I. Sorrentino, A. Piscitelli, and P. Giardina. (2020). Spotlight on Class I Hydrophobins: Their Intriguing Biochemical Properties and Industrial Prospects in Grand Challenges in Fungal Biotechnology. Educational Champions: Springer International Publishing : 333–347.

[46] I. Stanzione, R. Pitocchi, A. Pennacchio, P. Cicatiello, A. Piscitelli, and P. Giardina. (2022). Innovative surface bio-functionalization by fungal hydrophobins and their engineered variants. Frontiers in Molecular Bioscience. 9. 8. : 1-9.

[47] C. N. Muhonja, H. Makonde, G. Magoma, and M.

Imbuga. (2018). Biodegradability of polyethylene by bacteria and fungi from Dandora dumpsite Nairobi-Kenya. PLoS One. 13. 7. 1–17. 2018.

[48] V. Gambarini, O. Pantos, J. M. Kingsbury, L. Weaver, K. M. Handley, and G. Lear. (2021). Phylogenetic Distribution of Plastic-Degrading Microorganisms. mSystems. 6. 1.

[49] T. Matjašič, T. Simčič, N. Medvešček, O. Bajt, T. Dreo, and N. Mori. (2021). Critical evaluation of biodegradation studies on synthetic plastics through a systematic literature review. Science Total Environment. 752.

[50] S. Dey, U. Anand, V. Kumar, S. Kumar, and M. Ghorai. (2023). Microbial strategies for degradation of microplastics generated from COVID-19 healthcare waste. Environmental Research. 216. P1. : 114438.

[51] J. Yang, Y. Yang, W.-M. Wu, J. Zhao, and L. Jiang. (2014). Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. Environmental Science Technology. 48. 23. : 13776–13784.

[52] N. Priyanka and T. Archana, "Biodegradability of Polythene and Plastic By The Help of Microorganism: A Way for Brighter Future," J. Environ. Anal. Toxicol., vol. 1, pp. 1–4, 2011, doi: 10.4172/2161-0525.1000111.

[53] N. Atanasova, S. Stoitsova, T. Paunova-krasteva, and M. Kambourova. (2021). Plastic Degradation by Extremophilic Bacteria. International Journal of Molecular Science. 22. : 5610.

[54] P. H. Janssen, P. S. Yates, B. E. Grinton, P. M. Taylor, and M. Sait. (2022). Improved Culturability of Soil Bacteria and Isolation in Pure Culture of Novel Members of the Divisions Acidobacteria , Actinobacteria. Applied and Environmental Microbiology. 68. 5. : 2391–2396.

[55] A. Abdelfattah et al. (2023). Microalgae-based wastewater treatment: Mechanisms, challenges, recent advances, and future prospects. Environmental Science Ecotechnology. 13. : 100205.

[56] C. Cunha, M. Faria, N. Nogueira, A. Ferreira, and N. Cordeiro. (2019). Marine vs freshwater microalgae exopolymers as biosolutions to microplastics pollution. Environmental Pollution. 249. : 372–380.

[57] Y. R. Cheng and H. Y. Wang. (2022). Highly effective removal of microplastics by microalgae Scenedesmus abundans. Chemical Engineering Journal. 435. P2. : 135079.

[58] E. Syranidou et al. (2017). Development of tailored indigenous marine consortia for the degradation of naturally weathered polyethylene films. PLoS One. 12. 8. : 1–21.

[59] H. S. Auta, C. U. Emenike, and S. H. Fauziah. (2017). Screening of Bacillus strains isolated from mangrove ecosystems in Peninsular Malaysia for microplastic degradation. Environmental Pollution. 231. : 1552–1559.

[60] A. Helen Shnada. (2017). Screening of bacillus Strains Isolated from Mangrove Ecosystem in Penisular Malaysia for Microplastic Degredation. Environmental Pollution. 9. 43. : 1552-1559.

[61] P. F. Screening and P. Acid. (2017). Polymer Film-Based Screening and Isolation of Polylactic Acid (PLA)- Degrading Microorganisms. 27. : 342–349.

[62] K. Jain, H. Bhunia, and M. Sudhakara Reddy. (2018). Degradation of polypropylene–poly-L-lactide blend by bacteria isolated from compost. Bioremediation Journal. 22. 3–4. : 73–90.

[63] S. Skariyachan, A. A. Patil, A. Shankar, M. Manjunath, N. Bachappanavar, and S. Kiran. (2018). Enhanced polymer degradation of polyethylene and polypropylene by novel thermophilic consortia of Brevibacillus sps. and Aneurinibacillus sp. screened from waste management landfills and sewage treatment plants. Polymer Degradradatiin Stabilization. 149. 1. : 52–68.

[64] S. Y. Park and C. G. Kim. (2019). Biodegradation of micro-polyethylene particles by bacterial colonization of a mixed microbial consortium isolated from a landfill site. Chemosphere, 222. : 527–533.

[65] S. Habib, A. Iruthayam, M. Y. A. Shukor, S. A. Alias, J. Smykla, and N. A. Yasid. (2020) Biodeterioration of untreated polypropylene microplastic particles by antarctic bacteria. Polymers (Basel). 12. 11. : 2616.

[66] V. Zadjelovic et al. (2022). A mechanistic understanding of polyethylene biodegradation by the marine bacterium Alcanivorax. Journal Hazardous Material. 436. 6. : 129278.

[67] A. Paço et al. (2017). Biodegradation of polyethylene microplastics by the marine fungus Zalerion maritimum. Science Total Environment. 586. : 10–15.

[68] S. Khan et al. (2017). Biodegradation of polyester polyurethane by Aspergillus tubingensis. Environmental Pollution. 225. : 469–480.

[69] E. El-Morsy, H. Hassan, and E. Ahmed. (2017). Biodegradative activities of fungal isolates from plastic contaminated soils. Mycosphere. 8. 8. : 1071–1086.

[70] N. Ojha et al. (2017). Evaluation of HDPE and LDPE degradation by fungus, implemented by statistical optimization. Scientific Reports. 7. 1. : 1–13.

[71] N. Puspitasari, S. Tsai, and C. Lee. (2021). Fungal Hydrophobin RolA Enhanced PETase Hydrolysis of Polyethylene Terephthalate. Applied Biochemistry and Biotechnology. 193. : 1284–1295.

[72] F. Nouban and M. Abazid. (2017). Plastic degrading fungi Trichoderma viride and Aspergillus nomius isolated from local landfill soil in Medan. Iopscience. 8. 2. : 68–74.

[73] M. K. Sangale, M. Shahnawaz, and A. B. Ade. (2019). Potential of fungi isolated from the dumping sites mangrove rhizosphere soil to degrade polythene. Scientific Reports. 9. 1. : 1–11.

[74] V. K. Vivi, S. M. Martins-Franchetti, and D. Attili-Angelis. (2019). Biodegradation of PCL and PVC: Chaetomium globosum (ATCC 16021) activity," Folia Microbiol. (Praha). 64. 1. pp. 1–7.

[75] K. E. Kosiorowska, X. Po, G. Wang, and I. Borodina. (2021). International Biodeterioration & Biodegradation Efficient biodegradation of aliphatic polyester by genetically engineered strains of the yeast Yarrowia lipolytica. International Biodeterioration and Biodegradation. 161. 3. :

105213.
[76] Y. Sun et al. (2022). Enhancing microplastics biodegradation during composting using livestock manure biochar. Environmental Pollution. 306. 2.
[77] Č. Novotný and M. Mucha. (2022). Biodeterioration of Compost-Pretreated Polyvinyl Chloride Films by Microorganisms Isolated From Weathered Plastics. 10. 2. : 1–11.