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PLASTICS IN THE COLD MARINE ENVIRONMENT: A REVIEW OF THE POTENTIAL FOR MICROBIAL BIODEGRADATION

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ABSTRACT:

Background: Plastics are widely used due to their durability, flexibility, and transparency, leading to extensive industrial applications. However, the accumulation of plastics in various ecosystems has created significant environmental challenges.

Objective: This review aims to evaluate studies conducted over the past ten years on the biodegradation of plastics by microorganisms from cold marine environments.

Methods:

- **Descriptors Used**: "plastic biodegradation AND cold oceans," "plastic biodegradation AND (psychrophilic OR psychrophile)," "PETAse AND (fungi OR bacteria)," and "extremophiles AND plastic biodegradation."
- **Databases Searched**: Scopus, PubMed, and Google Scholar.
- **Number of Papers Located**: 11,481.
  - **PubMed**: 1.79%
  - **Google Scholar**: 1.84%
  - **Scopus**: 0.26%

Results:

- The genera most frequently mentioned as potential plastic degraders in cold marine habitats were Streptomyces, Corynebacterium, Arthrobacter, Micrococcus, Pseudomonas, and Rhodococcus.
- The findings indicate a significant gap in research on the degradation of plastics by microorganisms in cold environments.

Conclusion: There is a need for further studies to explore and enhance the activity of cold-adapted microbial enzymes for effective plastic biodegradation in cold ecosystems. This gap presents opportunities for additional research in this emerging field.

KEYWORDS: Plastic, Ocean, Extreme Environment, Bioremedy, Psychophiliacs, Plastic biodegradation, Cold-adapted microorganisms, Enzymatic degradation, Arthrobacter, Pseudomonas, Rhodococcus.

INTRODUCTION:

Plastic was first produced industrially in 1950 despite being used for a century. Around 7.8 billion tons of plastic had previously been produced worldwide as of 2015. At least 5.25 trillion microplastics, or plastic particles smaller than 5 mm, are thought to float in the world's oceans and weigh 268,940 tonnes. However, forecasts from the Ellen MacArthur Foundation suggest that production might increase up to four times by the end of 2050 and quadruple over the next 20 years. According to Urbanek et al., plastics are defined as polymeric materials or polymers that can transform into plastic conditions when heated and under pressure (Viel et al., 2023; Xiang, Bairoliya, Cho, & Cao, 2023).

Examples of polymeric materials include polyethene terephthalate (PET), polyethene (PE), high-density polyethene (HDPE), low-high-density polyethene (LDPE), polyvinyl chloride (PVC), polypropylene (PP), and polystyrene (PS). Numerous processes, such as improper sewage management and disposal, coastal landfill operations, and trash transportation to streams and rivers, result in the accumulation of these elements in the ocean. About 80% of the plastic discovered in the oceans comes from land, with the remaining 20% from shipping, tourism, fishing, and other businesses (Nabi, Zaheer, Jin, & Yang, 2023; Zhai, Zhang, & Yu, 2023).

Abiotic elements like temperature, oxygen, UV radiation, and physical stress cause plastic fragments in the marine environment. These bits of plastic waste, or microplastics, eventually reach subtropical gyres, spanning up to one million km2. Through ingestion and marine entanglement, plastic garbage causes harm to several creatures, including fish, sea turtles, birds, and marine mammals. The quantity of plastic seen floating in the open ocean is but a portion of the whole. Over two-thirds of plastic debris ends at sea level, with the remaining half washing up on beaches and the remaining floating at or below the surface (Nguyen et al., 2023; Omura et al., 2024).

"Conditioning film" is the term used to describe the organic and inorganic debris that covers plastics in maritime environments. Microorganisms use this film as a source of carbon and nutrients, quickly colonizing its surface to form a biofilm. One gram of marine sediment can contain hundreds of millions of bacterial cells, demonstrating the enormous diversity and quantity of microorganisms in marine habitats. Cold-adapted communities have evolved special metabolic processes that allow cells to adapt to low temperatures, scarce nutrient availability, and high salinity conditions that necessitate both structural and functional adaptations for survival (Margesin and Miteva) (Ghosh, Qureshi, & Purohit; Lv, Li, Zhao, & Shao, 2024).

Research centred on bioprospecting has shown interest in psychrophilic and psychotolerant microorganisms to investigate this enzymatic arsenal distinct from terrestrial and mesophilic bacteria. Studies employing plastic samples from the ocean or plastic tested in an experimental marine environment have revealed several microbiological lineages, including bacteria and fungi. Thus, the genera Aspergillus, Penicillium, Fusarium; Enterobacter, Pseudomonas, Acinetobacter; Clostridium, Ralstonia, Bacillus, Comamonas, Stenotrophomonas, and Aspergillus might be mentioned (Idris et al., 2023; Rüthi, Cerri, et al., 2023).

Abiotic (physical and chemical) plastic degradation that weakens the polymer is necessary for biodegradation. Sunlight, heat, humidity, and chemical conditions that can disrupt the polymer chain can all trigger this abiotic process. Four stages make up the microbial biodegradation of plastic, as defined by Dussud & Ghiglione: i) Biodeterioration: microorganisms that adhere to the plastic surface (cohesion), form a biofilm, and release extracellular polymeric substances (EPS). The accumulation of these EPS between abiotically induced fractures and pores exacerbates the disintegration of chemical bonds and pores. As a result, chemolithotrophic bacteria release acidic compounds like nitrous, nitric, or sulfuric acid, and chemoorganotrophic communities produce organic acids, which promote the progressive degradation of the plastic matrix (Leistenschneider et al., 2023; Wu et al., 2023).

Table 1: Historical and Forecasted Plastic Production

Year	Event/Forecast	Reference
1950	First industrial production of plastic	Viel et al., 2023; Xiang, Bairoliya, Cho, & Cao, 2023
2015	7.8 billion tons of plastic produced worldwide	Viel et al., 2023; Xiang, Bairoliya, Cho, & Cao, 2023
2015	5.25 trillion microplastics in the oceans weighing 268,940 tonnes	Viel et al., 2023; Xiang, Bairoliya, Cho, & Cao, 2023
2050	Production might increase up to four times by 2050	Ellen MacArthur Foundation
2040	Production could quadruple over the next 20 years	Ellen MacArthur Foundation

Table 2: Definition and Examples of Polymeric Materials

Term	Definition	Examples	Reference
Plastics	Polymeric materials that transform under heat and pressure	Polyethylene terephthalate (PET), polyethene (PE), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS)	Urbanek et al., Viel et al., 2023; Xiang, Bairoliya, Cho, & Cao, 2023

Table 3: Sources of Ocean Plastic Pollution

Source of Pollution	Percentage	Reference
Land	80%	Nabi, Zaheer, Jin, & Yang, 2023; Zhai, Zhang, & Yu, 2023
Shipping, tourism, fishing, other businesses	20%	Nabi, Zaheer, Jin, & Yang, 2023; Zhai, Zhang, & Yu, 2023

Table 4: Impact of Plastic Fragments on Marine Life

Abiotic Factors	Description	Reference
Temperature, Oxygen, UV radiation, Physical stress	Cause plastic fragments in the marine environment leading to microplastics	Nguyen et al., 2023; Omura et al., 2024

Impact on Marine Life	Description	Reference
Ingestion and marine entanglement	Causes harm to fish, sea turtles, birds, and marine mammals	Nguyen et al., 2023; Omura et al., 2024

Table 5: Colonization and Adaptation of Microorganisms on Plastic

Term	Description	Reference
Conditioning film	Organic and inorganic debris covering plastics, used by microorganisms as carbon and nutrient sources	Margesin and Miteva
Biofilm formation	Microorganisms quickly colonize the plastic surface to form a biofilm	Ghosh, Qureshi, & Purohit; Lv, Li, Zhao, & Shao, 2024

Table 6: Bioprospecting and Microbial Lineages

Research Focus	Description	Example Genera	Reference
Bioprospecting	Psychrophilic and psychrotolerant microorganisms for distinct enzymatic activity	Aspergillus, Penicillium, Fusarium, Enterobacter, Pseudomonas, Acinetobacter, Clostridium, Ralstonia, Bacillus, Comamonas, Stenotrophomonas, Aspergillus	Idris et al., 2023; Rüthi, Cerri, et al., 2023

Table 7: Stages of Microbial Biodegradation of Plastic

Stage	Description	Reference
Biodeterioration	Microorganisms adhere to the plastic surface, form a biofilm, release extracellular polymeric substances (EPS)	Leistenschneider et al., 2023; Wu et al., 2023
Fragmentation	Enzymes (oxygenase, lipase, esterase) break down the polymer into oligos and monomers	Leistenschneider et al., 2023; Wu et al., 2023
Assimilation	Plastic monomers are internalized through transporters or passively through the membrane	Leistenschneider et al., 2023; Wu et al., 2023
Mineralization	Monomers are broken down by oxidation through aerobic, anaerobic respiration, or fermentation, producing CO2, N2, CH4, H2O	De Jesus & Alkendi, 2023; Kim et al., 2023

ii) fragmentation: this phase involves the polymer being broken down into oligos and monomers by the enzyme's oxygenase, lipase, and esterase, thereby completing the breakdown of the polymer. These reactions primarily take place at the ends of the polymer (cracks and pores); iii) assimilation: this happens when certain transporters internalize plastic monomers or when they passively pass through the membrane and cell wall; iv) mineralization: after internalization, the monomers are broken down by oxidation by three possible metabolic pathways, which include aerobic, anaerobic respiration, or fermentation, depending on the type of microbe. CO2, N2, CH4, and H2O are examples of oxidized secreted metabolites (Figure 1) (De Jesus & Alkendi, 2023; Kim et al., 2023).

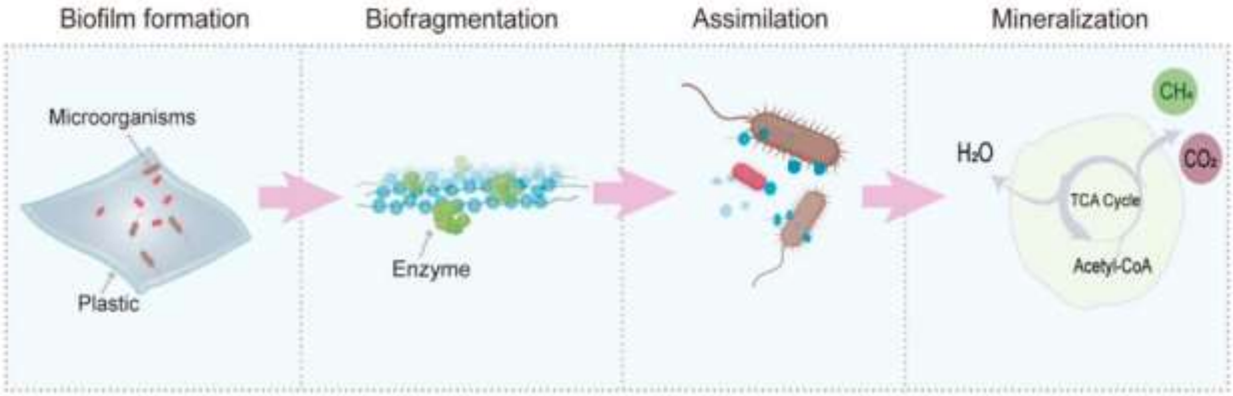

Figure 1 - The different stages of biodegradation of plastic by microorganisms.

MINERALIZATION:

Extreme and understudied ecosystems, such as polar regions, intricate marine habitats, and hyperthermal conditions, have been the subject of research in recent years. Identifying novel bioactive chemicals of interest and their potential use in industrial and healthcare processes are the primary goals of these studies. Plastic waste can be discovered in deep-sea sediments and on the surface of the Antarctic marine system, commonly referred to as the Southern Ocean. Microplastics were detected in high concentrations in these areas, with counts ranging from 16 to 766 artificial particles per square meter. Numerous marine strains of Pseudomonas pertucinogena have been reported to grow at temperatures below 15°C and to be tolerant of moderate salt concentrations, indicating their adaptability to cold conditions (Sciscione, Hailes, & Miodownik, 2023; Zhang et al., 2024).

A few of the reported species have symbiotic relationships with sponges and aquatic plants. These marine bacteria appear to have contaminated environments as one of their homes in addition to these substrates. Some researchers have referenced the enzymes produced by the P. pertucinogena bacterium, primarily in works on synthesizing chiral compounds and the breakdown of polymers. Recently, Haernvall et al. showed that P. pelagia can efficiently break down phthalic acid-based ionic polyesters in a study where the lipase biocatalyst enzyme was the cause of the degradation (Chigwada & Tekere, 2023; Royer, Greco, Kogler, & Deheyn, 2023).

Therefore, scholarly publications published during the previous ten years that discussed the application of microbes from cold marine settings in the processes of degradation and assimilation, or even the comprehension of microbial metabolism connected to plastic, were used to conduct this review (Okoth, Makonde, Bosire, June Mwajuma, & Kibiti, 2023).

METHODOLOGY:

A qualitative analytical-exploratory technique was employed to conduct this research using digital scientific literature databases, such as PubMed, Scopus, and the Google Scholar search engine. Data from November 2010 to November 2022 were considered in the following ways: A list of keywords that the authors had allocated based on the research goals was utilized to search through the databases' contents. Peptase AND (fungi OR bacteria), "plastic biodegradation AND (psychrophile OR psychrophile)", and "extremophile AND plastic biodegradation" were the descriptors that were thus employed (Caruso et al., 2023; Rognan, 2023).

After defining the search criteria, filters were used to exclude results gathered from publications such as conference publications, annual events, master's and doctoral theses, course completion works, monographs, and the time curve between 2010 and 2022. It was suggested that journals with low impact factors be eliminated, so to complete this work, we took into account impact factor indices (JCR - Journal Citation Reports) higher than 2.0 in addition to the selection of the research themes "Environmental Science," "Chemical and Biochemical Engineering," and "Genetics and Molecular Biology" (the remaining areas presented works not relevant for this study) (Dodhia et al., 2023; Lee et al., 2024).

The data about scientific publications was gathered and organized into tables, where the number of publications found using the keywords and the total number after the cuts were made were correlated (Orlando et al., 2023).

RESULTS AND DISCUSSION:

Eleven thousand four hundred eighty-one scientific works were discovered in the databases, and the search tool was used after looking for publications within the specified time frames. The number of works was then decreased to 105 (Table 1) after a selection of works was made using the filters suggested in this methodology, such as a time curve between the years 2010 and 2022 and impact factor indices (JCR over 2.0) (Hakvåg, Brakstad, Kubowicz, & Booth, 2023).

DESCRIPTORS	PUBMED	GOOGLE SCHOLAR	SCOPUS	JCR (>2.0)
Plastic biodegradation AND cold oceans	12	7000	158	24
Extremophile AND plastic biodegradation	14	2120	13	24
Plastic biodegradation AND (Pschychrophile OR Pschychrophilic)	3	2080	30	35
PETases AND (bacteria OR fungus)	1	40	10	22
TOTAL	30	11240	211	105

Table 1 - Scientific articles found with the Scopus, NCBI and Google Scholar descriptors.

Table 1 shows that a search on Google Scholar yielded the most results (n = 11,240), followed by searches on Scopus and Pubmed (n = 211 and 30, respectively). The fact that the research on Google Scholar is non-specific and encompasses all forms of research in the categories assessed explains why the amount there is significantly higher. Table 2 was created, considering every filter that was applied to the study, aiming to showcase the top five scientific publications for each description. The information in the table briefly displays the following points: authors, strains utilized in the study, year of publication, journal, JCR, and database(s) or search engine where the work was located (Kour et al., 2023; La Fuente, Maniglia, & Tadini, 2023).

PUBLICATION YEAR	PERIODICAL	AUTHORS	JCR	GENUS/SPECIES INVESTIGATED	DATABASE
“Plastic Biodegradation AND (Psychrophile OR Psychrophilic)”					
2020	Gene	Rogala et al.	3.8	Bactérias produtoras de PHA	PubMed
2010	Water Research	Trzcinski, & Stuckey	9.13	não revelado	Google Scholar and Scopus
2019	Photosynth Res	Cook et al.	3.21	Chlamydomonas spp.	PubMed
2013	International Biodeterioration & Biodegradation	Singh et al.	4.07	Pseudomonas sp. GBS.5	Scopus
2011	JAMSTEC Rep Res Dev	Sekiguchi et al.	3.2	Shewanella, Moritella, Psychrobactere Pseudomonas	Google Scholar
“Plastic Biodegradation AND Cold Oceans”					
2010	Journal of Japanese Society for Extremophiles	Sekiguchi et al.	2.57	Shewanella, Moritella, Psychrobacter e Pseudomonas	Google Scholar
2013	Marine Pollution Bulletin	Harshvardhan & Bhavanath	4.05	Kocuria palustris M16, Bacillus pumilus M27 e Bacillus subtilis H1584	Google Scholar and Scopus
2019	Marine Pollution Bulletin	Xu et al.	4.05	Alphaproteobacteria e Gammaproteobacteria	Scopus
2017	Science of the Total Environment	Paço et al.	6.55	Zalerion maritimum	
2022	Marine Environment Research	Giacomucci et al.	2.7	Clostridium, Acetobacterium Dethiosulfovibrio. e Sporobacter	
"Extremophile AND Plastic Biodegradation”					
2018	International Journal of Advanced Scientific	Rafiq et al.	2.57	Halobacterium salinarium, Halobacillus salinus, Vibrio	

	Research and Management			fischeri, Aeromonas spp. e Staphylococcus epidermidis.	
2011	Applied Microbiology and Biotechnology	Dastgheib et al.	4.05	Dastgheib et al. Marinobacter e Halomonas	
2018	RSC Advances	Chauhan et al.	4.05	Exiguobacterium sibiricum dr11e Exiguobacterium undae dr14	
	Journal of Applied Phycology	Ouada et al.	6.55	Chlorophyta picocystis e Chlorophyta Graciela	
2011	Jamstec Rep Res Dev	Sekiguchi et al.	2.7	Shewanella, Moritella, Psychrobactere seudomonas	Google Scholar
“Petases AND (Bacteria OR Fungus)”					
2020	Process Biochemistry	Costa et al.	2.95	Yarrowia lipolytica	Scopus
	Process Biochemistry	Carniel et al.	2.95	Candida antarctica e Humicolainsolent	Scopus
2019	Nature Communications	Joo et al.	12.12	Ideonella sakaiensis 201-F6	Google Scholar
2022	Frontiers inMicrobiology	Almeida et al.	4.23	Streptomyces sp. SM14	PubMed
2020	Journal of Environmental Chemical Engineering	Kumar et al.	4.3	Rhococcus sp. SSM1	Scopus

Table 2 - List the five most relevant papers for each descriptor used in this review.

Following a more thorough examination of the published works, reports of the application of plastic-degrading microorganisms in marine environments were observed. These reports included those by Sekiguchi et al. and Xu et al., as well as reports on the degradation of microplastics (PCL) found in China's coastal seas by members of the taxonomic groups Alphaproteobacteria, Rhodobacteraceae, and Gammaproteobacteria. Even though this data was retrieved using the description "plastic biodegradation AND cold oceans," none of the microbes included above are psychrophilic. However, most of the microbes documented in the literature are from areas with year-round temperature fluctuations and cold and hot seasons (Chen et al., 2023).

Most of the studies were related to the use of microorganisms from cold environments in the digestion processes of various waste types, including organic, industrial, wastewater, and manure, as well as various works related to bioremediation of soil contaminated by petroleum, organic compounds, chlorinated pollutants, pharmaceuticals, and others. This was observed using the descriptor "Plastic biodegradation E (Psychrophilic OR Psychrophilic)". Figure 2 summarizes the most pertinent applications that were discovered, with the most often observed usage in the study being the bioremediation of other polluting substances (Meyer Cifuentes et al., 2023; Rüthi, Rast et al., 2023).

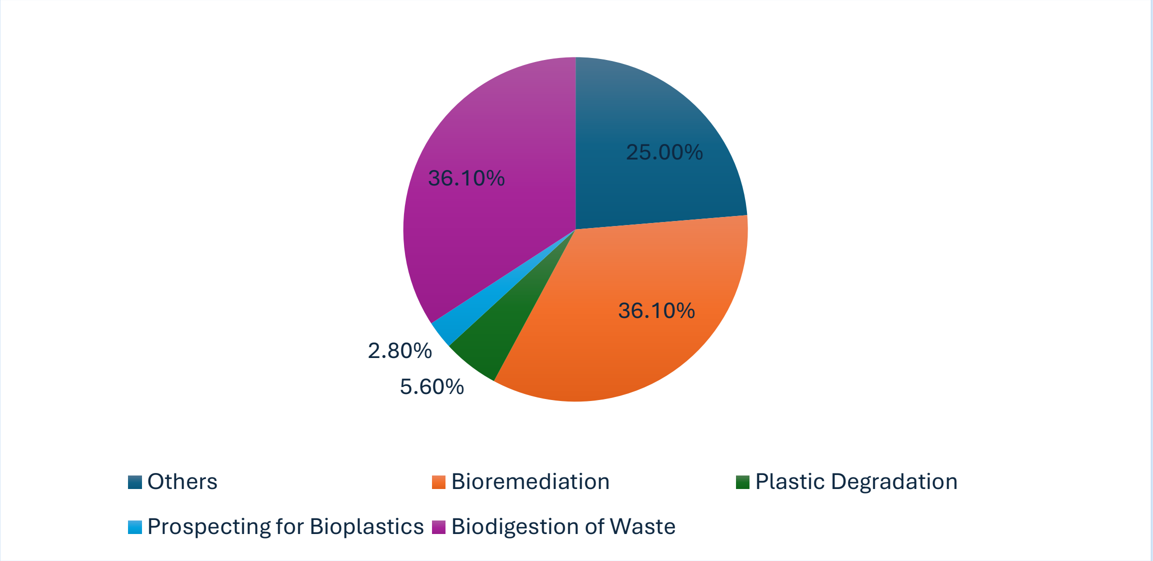

Figure 2 - Research applications found with the combination “Plastic biodegradation E (psychrophile OR psychrophile)”.

Regarding the research utilizing the descriptor "PETase AND (bacteria OR fungi)", it was able to see studies that employed combinations of multiple microorganisms to assess PET hydrolysis among the 22 chosen works. According to Carniel et al.'s research, isolates of Candida antarctica and Humicola insolens demonstrated the ability to hydrolyze PET synergistically, meaning that H. insolens could not complete the hydrolysis reaction without the yeast C. Antarctica's complementary action (Maheswaran et al., 2023; Mallick, Sahu, Dubey, & Das, 2023).

The synergistic activity of isolates of Marinobacter, Pseudooceanicola, and Saccharospirillum in the degradation of PET samples was also investigated by Meyer-Cifuentes et al., who discovered that hydrolysis only leads to the association of the bacteria. Research on microbial combinations has shown promise since certain strains can break the links in plastic polymers but cannot ingest or decompose the polymers themselves; other microbial strains working together can accomplish this. Since it will be possible to move toward the applicability of these results by better understanding the mechanisms, structures, and biological roles of the enzymes that degrade plastic, all of this research represents significant advances forward in the field of plastic degradation (Li et al., 2023; Omidoyin & Jho, 2023).

Similarly, it was feasible to find little research on the breakdown of plastics using extremophilic microbial cells by using the description "Extremophilic AND plastic biodegradation" in the search. The great majority of the works focused on research aimed at enhancing the production of compounds produced by extremophilic microorganisms, such as bioplastic polyhydroxyalkanoates (PHA), bioremediation, the use of extremophilic plants, biogas production, and plastic as a vector for the spread of antibiotic resistance. Only articles devoted to the biodegradation of plastics could be located using the Google Scholar search engine; these searches turned up descriptions of halophilic and halotolerant microbes that could produce enzymes that broke down polymers (Sahu, Kaur, Khatri, Singh, & Arya, 2023; Vaksmaa et al., 2024).

Rafiq et al. examined eleven strains that were able to produce the enzymes needed to break down low-density polyethylene (LDPE), including Vibrio fischeri, Halobacterium salinarium, Halobacillus salinus, Aeromonas spp., and Staphylococcus epidermidis. Two strains of Exiguobacterium sibiricum DR11 and Exiguobacterium undae DR14 that may be able to biodegrade polystyrene (PE) were also assessed by Chauhan et al. E. undae was able to use polystyrene as a carbon source in this investigation. The first investigation to document bacteria that break down polycaprolactone (PCL) that was isolated from the deep sea (5 km) was conducted by Sekiguchi and associates (Pant & Valapa, 2023; Suzuki et al., 2023).

In studies of plastic polymer degradation, the authors assessed microbial strains; however, they only received data regarding the degradation of PCL biodegradable plastic by strains belonging to the genera Shewanella, Moritella, Psychrobacter, and Pseudomonas. However, Urbanek et al. state that the microorganisms isolated from cold environments that are most cited in scientific works are species of the genera Pseudomonas, Streptomyces, Corynebacterium, Arthrobacter, Micrococcus, and Rhodococcus. These microorganisms can also produce enzymes that may be used to degrade plastic materials, such as lipases (Sutkar, Gadewar, & Dhulap, 2023).

Understanding the primary research limitations is important before comprehending the challenges associated with plastic biodegradation. Because of low ambient temperatures, low energy consumption, and a lack of sunlight, degradation rates can be much lower in cold climates and at the bottom of the ocean. Since UV light is essential for starting the oxidative process, restricted exposure might have the biggest effect (O'Brien & Thompson). Moreover, the oxygen content of the sea floor can be extremely low, making it unlikely that the essential oxidative metabolic processes will occur there (Xiang et al., 2023).

Data regarding the rate at which plastic is mineralizing in the oceans must be available. Smaller discoveries, such as the visualization of pits in bacterial cell-shaped plastic debris found in the marine environment and the identification of a set of xenobiotic degradation genes present in microbial communities found in the marine environment, are nevertheless extremely significant for future research—a biofilm developed around the plastic, which caused the plastic to deteriorate. Since microbial biodegradation might entail complex microbial communities, it is essential to thoroughly understand the metabolic pathways engaged in the process, i.e., to research co-metabolic pathways. Standard protocols must be created to assess plastic's biodegradation, as many approaches are used in the existing research, which makes it challenging to realistically and statistically compare the outcomes (Vaksmaa et al., 2024).

CONCLUSION:

Plastic pollution and environmental harm have raised awareness of the issue and prompted more studies into potential remedies. Examining the studies included in this review, it was feasible to observe that, even with the identification of degrading strains and several advancements in the field, there is still more work to be done before biological systems can be effectively applied to cure ocean plastic pollution. The metabolic pathways and genes involved in the biodegradation of plastic polymers by microorganisms in cold conditions remain largely unexplored. The isolation of microorganisms from cold environments, functional screening, and the potential development of novel techniques to characterize polluting compounds and their metabolites are all made possible by this bibliographic work, which also expands our knowledge of the psychrophilic, marine or psychrotolerant microbiota that metabolize and degrade plastic polymers.

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