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"Microbial And Insects Based Approaches To Plastic Degradation: A Review Of Recent Advances And Challenges"

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Abstract : Plastic waste constitutes a profound and escalating threat to ecosystems, environmental integrity, and public health. In a notable study conducted within the Great Pacific Garbage Patch, researchers from the Royal Netherlands Institute for Sea Research identified Parengyodontium album, a fungal species with the capacity to degrade polyethylene (PE) upon activation by ultraviolet (UV) radiation. UV exposure not only induces photochemical weakening of polymeric structures but also enhances their susceptibility to microbial degradation. Nevertheless, under controlled laboratory conditions, P. album demonstrates limited efficacy, primarily targeting surface-bound polymers and proceeding at a notably slow degradation rate.

The exploration of microbially mediated plastic degradation is fraught with complexities, stemming from the heterogeneity of polymer structures, variable environmental conditions, and methodological limitations in tracking biodegradation. Conventional analytical techniques, such as gravimetric analysis and spectroscopy, often fall short in accurately tracing the assimilation of polymer-derived carbon into microbial biomass.

An alternative avenue has emerged through the biological capabilities of wax worms (Galleria mellonella), which can degrade polyethylene via phenol oxidase enzymes found in their saliva. This discovery has catalyzed interest in enzyme-driven recycling strategies, highlighting their potential scalability and efficiency as viable solutions for plastic waste remediation.

Despite the promise of microbial degradation, its implementation on an industrial scale remains constrained. The process is highly dependent on environmental variables, including temperature and polymer composition. Consequently, intensified research efforts are required to enhance the efficiency of biodegradation processes, evaluate their ecological ramifications, and develop robust biotechnological platforms for sustainable and effective plastic waste management.

Index Terms -: *P. album*, wax worm , poly ethylene, The Royal Netherlands Institute for Sea Research (NIOZ), UV, enzyme.

I. INTRODUCTION:

Plastic is integral to contemporary society, owing to its exceptional versatility and cost-effectiveness. Nevertheless, its excessive consumption and improper disposal have given rise to significant environmental challenges. Conventional plastic waste management techniques, such as landfilling and incineration, are increasingly recognized for their environmental drawbacks and limited long-term efficacy, thereby necessitating the development of innovative and sustainable alternatives. Among these, biologicallydriven strategies—particularly those involving microorganisms and insect-based systems—have emerged as promising avenues for the natural degradation of synthetic polymers. These approaches utilize the enzymatic capabilities of specific organisms to facilitate the breakdown of plastic materials, potentially contributing to environmental remediation efforts. This paper aims to investigate recent advancements in microbial and insect-mediated plastic degradation, while also addressing the scientific and practical barriers that impede their large-scale implementation.

Researchers have identified a plastic-degrading fungus, *Parengyodontium album*, actively consuming portions of plastic waste within the Great Pacific Garbage Patch—a region also characterized by dense microbial colonization. The assessment of microbial plastic degradation remains methodologically complex, with significant limitations that hinder consistent evaluation and comparison across studies. Numerous factors influence the efficiency of microbial degradation, including the particle size of the plastic, the physicochemical properties of the polymer—such as crystallinity, degree of crosslinking, and the presence of chemical additives—as well as environmental or incubation conditions. Among the most commonly employed analytical techniques are Fourier-transform infrared (FTIR) spectroscopy, which is used to detect polymer oxidation, and gravimetric analysis, which measures the weight loss of polymer samples over time. Despite their widespread application, these methods offer only partial insights into the underlying biodegradation mechanisms and the extent of microbial assimilation.

Moreover, the progressive fragmentation of plastic materials and the subsequent development of microbial biofilms on polymer surfaces have been visualized through advanced imaging techniques such as scanning electron microscopy (SEM) and laser scanning confocal microscopy (LSCM). While these methodologies provide valuable structural and morphological insights, they are often limited by low sensitivity, labor-intensive protocols, and an inability to distinguish between biotic and abiotic degradation mechanisms. Furthermore, these techniques are not suitable for quantifying microbial degradation rates, nor do they allow for the direct tracing of carbon flux from polymer substrates into degradation byproducts or microbial biomass—an essential indicator for unequivocal confirmation of true biodegradation processes..

1. Sources of Plastic Waste

Plastic pollution has emerged as a critical global environmental concern. While public awareness of the issue is widespread, the full scope of the problem is often underestimated. According to recent estimates, approximately 350 million metric tons of plastic waste are generated annually. Projections suggest that, in the absence of significant intervention, this figure could potentially triple by the year 2060, exacerbating ecological degradation on a global scale.

1.1 Common Sources of Plastic Waste

The most prevalent sources of plastic pollution are frequently everyday consumer products—items routinely encountered in urban environments, along coastlines, and within natural ecosystems. A fundamental step toward mitigating plastic pollution involves the identification of these primary contributors and the adoption of sustainable practices aimed at minimizing personal reliance on single-use plastics.

1.1.1 Food Packaging and Wrappers

Environmental research indicates that food packaging, particularly single-use wrappers, accounts for nearly one-third of global plastic pollution. Discarded items such as candy wrappers and snack packaging are among the most commonly found debris. To combat this, individuals are encouraged to reconsider the environmental implications of improper disposal and to prioritize the consumption of products that utilize recyclable or reusable packaging materials.

1.1.2 Bottle and Container Caps

Caps from beverage containers, such as milk jugs and soda bottles, represent a significant portion of global plastic waste, contributing to over 10% of observed environmental pollution. As with other single-use plastic items, a practical and sustainable response lies in transitioning toward reusable packaging solutions, particularly refillable water bottles, which can substantially reduce dependence on disposable plastic caps.

1.1.3 Plastic Bags

Plastic bags have long symbolized the broader challenge posed by single-use plastics and remain one of the most pervasive pollutants. Their lightweight nature allows them to be easily transported by wind and water, often resulting in their accumulation in aquatic ecosystems, where they pose threats to marine life. The adoption of durable, reusable shopping bags offers a straightforward and impactful strategy to reduce plastic bag waste.

1.1.4 Plastic Stirrers and Straws

Plastic stirrers and straws, though seemingly minor in size and utility, contribute disproportionately to environmental degradation—accounting for approximately 10% of plastic waste in some regions. This has prompted numerous governments to implement bans or restrictions on their use. Consumers are encouraged to forgo straws when possible or to opt for sustainable alternatives, such as those made from metal, bamboo, or biodegradable materials.

1.1.5 Plastic Bottles

Plastic beverage bottles constitute an estimated 5–8% of total plastic waste worldwide. As with caps and lids, the most effective mitigation strategy involves replacing single-use bottles with reusable alternatives. Institutional initiatives, such as the installation of water bottle refill stations in workplaces, schools, and public areas, can further support systemic reductions in plastic bottle usage.

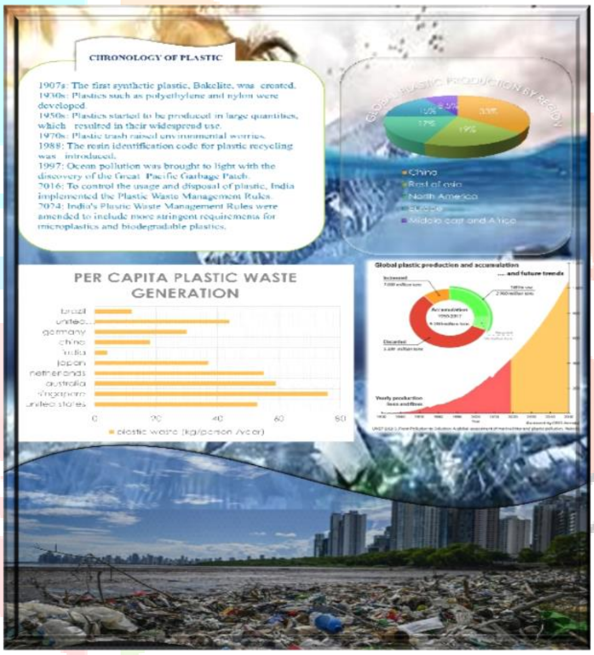

Fig.1 The background, effects, and necessity of sustainable management of plastic.

1.1.6 Takeout Food Containers

Takeout containers—comprising foam, plastic, and coated paper variants—constitute a substantial source of disposable waste in both urban and coastal environments. These single-use items contribute significantly to landfill overflow and marine pollution. A practical approach to mitigating this impact involves proactive consumer behavior, such as notifying food vendors in advance of one's intention to bring reusable containers for takeout orders, thereby reducing dependency on disposable packaging.

2. Microbial Plastic Degradation: The Role of Fungi

Recent scientific advancements have highlighted the potential of microbial agents in addressing the plastic pollution crisis. Specifically, the marine fungus *Parengyodontium album* has demonstrated the capacity to degrade polyethylene (PE), the most prevalent form of plastic waste found in marine environments. This fungal species thrives in microbial biofilms on plastic debris within oceanic gyres, such as the Great Pacific Garbage Patch.

Research conducted by marine microbiologists at the Royal Netherlands Institute for Sea Research (NIOZ)

reveals that *P. album* is capable of breaking down PE only after it has been exposed to ultraviolet (UV) radiation. According to researcher Linda Vaksmaa, "In the lab, *P. album* only degrades polyethylene that has been at least momentarily exposed to UV light. This implies that in natural marine settings, the fungus is limited to degrading plastic that initially floats near the surface, where it is exposed to sunlight." The findings suggest that UV radiation not only enhances biological degradation by marine fungi but also induces mechanical fragmentation of plastic materials, thereby accelerating the overall breakdown process. [1]
Despite increased efforts to address the plastic waste crisis, global plastic production continues to rise at an alarming rate. According to data from Plastics Europe, an industry association of plastic producers, annual plastic production has surged from 1.7 million metric tons in 1950 to nearly 390 million metric tons in 2021. Alarmingly, less than 10% of global plastic waste is currently recycled, underscoring the urgent need for alternative and scalable waste management strategies. [2]

3. **Plastic Degradation by Wax Worms (*Galleria mellonella*)**

The larvae of *Galleria mellonella*, commonly referred to as wax worms, have garnered scientific interest for their remarkable ability to degrade polyethylene (PE)—one of the most chemically resilient and widely produced synthetic polymers. Initial observations revealed that these larvae could not only ingest PE but also chemically decompose it at an unprecedented rate. This phenomenon is attributed to enzymes present in the worms' saliva, particularly phenol oxidases, which are capable of oxidizing long-chain carbon-based substances such as beeswax and plastic—compounds with similar structural characteristics.
Rather than relying on large-scale cultivation of the larvae, a more practical and scalable approach involves isolating, extracting, and cloning these enzymes for targeted plastic degradation applications. As noted by Dr. Federica Bertocchini, a leading researcher in the field, the long-term vision includes the development of enzyme-based solutions for domestic or industrial use. These could take the form of water-based enzymatic treatments designed for integration into waste processing facilities or at-home plastic degradation kits. The enzymatic breakdown of PE would ideally result in byproducts such as alcohols or ketones—naturally occurring and environmentally benign substances suitable for repurposing or safe disposal.
While the widespread application of wax worm-derived enzymatic degradation may still be years away, this research represents a critical advancement in sustainable waste management strategies. It underscores the potential of bio-recycling—where naturally occurring organisms and biochemical processes are harnessed to convert waste materials into valuable resources. As public awareness grows and technological refinement continues, such bio-based methods may play a pivotal role in the global shift toward environmentally responsible plastic waste solutions.
The applied significance of this discovery is further underscored by the characterization of microbial strains involved in similar biodegradation processes. These strains belong to genera already documented for their potential in plastic bioremediation. Although comprehensive evidence remains limited, numerous bacterial and fungal taxa exhibit putative plastic-degrading capabilities across a spectrum of high-molecular-weight synthetic polymers, including polyamide, polystyrene, polyvinyl chloride, and polypropylene. In contrast, the degradation of polylactic acid (PLA)—a synthetic biopolymer—has shown clear evidence of microbial decomposition. Notably, the microorganisms implicated in PLA degradation display conserved phylogenetic traits, suggesting evolutionary specialization in polymer breakdown. [3][4]

Parengyodontium album: mechanism and environmental potential

Mechanism of Action

- *Parengyodontium album* facilitates the biodegradation of plastic through a synergistic process initiated by ultraviolet (UV) radiation from sunlight. UV exposure causes preliminary photo degradation of plastic polymers, thereby enhancing their susceptibility to biological breakdown.
- The fungus secretes specific enzymes capable of hydrolyzing long-chain polymeric molecules into smaller, more manageable molecular fragments.

- During the degradation process, carbon dioxide is released as a byproduct in quantities comparable to those produced through normal human respiration.

Habitat and Discovery

- *P. album* was identified within the Great Pacific Garbage Patch, a prominent accumulation zone for marine plastic waste.
- It resides within the biofilms that form on the surface of oceanic plastic debris, existing in conjunction with diverse microbial communities.

Potential for Marine Pollution Mitigation

- The fungal species holds promise as a component of integrated bioremediation strategies, especially when used in concert with other plastic-degrading microorganisms and complementary environmental technologies.
- Despite its potential, the natural degradation rate of plastic by *P. album* is relatively slow, indicating that large-scale remediation of oceanic plastic pollution would require extended timeframes and multifaceted approaches.

II. METHODS AND METHODOLOGY

1. Isolation and Identification of Microorganisms

Microbial samples were collected twice over a two-month period (May and June) from the air within storage rooms housing the Wawel Arrases. The ambient environmental conditions during sampling were controlled, with temperatures maintained between 18–19 °C and relative humidity ranging from 47–48%. The passive sedimentation method was employed for microbial collection at various designated locations throughout the storage rooms.

Two types of culture media were utilized for microbial cultivation: Rose Bengal Agar (composed per liter of solution as follows—peptone: 5 g, glucose: 10 g, KH_2PO_4: 1 g, $MgSO_4 \cdot 7H_2O$: 0.5 g, Rose Bengal: 0.05 g, agar: 15.5 g) and Potato Dextrose Agar (PDA). Petri dishes were exposed to air by removing the lids for 20 to 30 minutes to facilitate airborne microbial deposition.

The fungus *Parengyodontium album* was isolated from biofilms coating plastic fragments collected during a scientific expedition to the North Pacific Subtropical Gyre. The initial objective was to assess the potential of *P. album* to biodegrade polyethylene (PE). To determine the rate of PE mineralization mediated by the fungus, both untreated and UV-irradiated ^13C-labeled polyethylene samples were incubated with *P. album*. The metabolic pathway of the ^13C-labeled carbon from the polymer matrix to its terminal oxidation product (CO_2) was monitored. Additionally, to trace the assimilation of PE-derived carbon into fungal biomass, nanometer-scale secondary ion mass spectrometry (nanoSIMS) was employed, alongside stable isotope analysis of fatty acid methyl esters (FAMEs).

2. Assessment of Antimicrobial Zeolites (Ag and Zn-Exchanged Forms)

To evaluate the potential of metal-exchanged zeolites as microbial growth inhibitors, two types of zeolites—Y and ZSM-5—were impregnated with silver (Ag) or zinc (Zn) ions. A total of 0.462 g of metal-exchanged zeolite was added to 5 mL of deionized water within polymeric weighing containers. Using sterilized tweezers, 1 × 2 cm sections of textile material were immersed in the zeolite suspension, with the process repeated three times to ensure uniform deposition.

Post-treatment, the materials were dried under sterile conditions in a laminar airflow cabinet. Once fully dried, the samples were transferred onto water agar plates using sterile tools. Each textile specimen was inoculated with a defined microbial strain, while control samples consisted of untreated fabric without any zeolite additive.

3. Statistical Analysis

Each experimental condition was replicated a minimum of four times to ensure reproducibility and statistical reliability. Data analysis was performed using Statistica software (Version 10, Stat Soft, USA). Statistical significance between control and treated groups was assessed using either Student's *t*-test or one-way analysis of variance (ANOVA), depending on the experimental design. A *p*-value of less than 0.05 ($p < 0.05$) was considered indicative of a statistically significant difference. [5]

Supplementary Research Developments

- Ongoing scientific investigations are exploring the mechanisms by which plastic degradation occurs in the deeper strata of the ocean, where light and oxygen levels are significantly reduced. These studies aim to understand the ecological dynamics and metabolic capabilities of microorganisms in such extreme environments.
- Concurrently, researchers based in Hawaii are engaged in the selective training and adaptation of marine fungi to enhance their capacity for consuming and metabolizing oceanic plastic debris. This bioengineering effort seeks to optimize the fungi's enzymatic pathways for more efficient plastic degradation under variable marine conditions.
- Furthermore, scientists are actively examining the potential to harness the plastic-degrading abilities of *Parengyodontium album* as a component of future large-scale ocean cleanup strategies. This includes the development of biotechnological applications that could utilize fungal agents in tandem with other microbial or mechanical remediation techniques. [6]
- In the pursuit of novel biodegradative organisms, researchers are also conducting deep-sea expeditions to isolate and characterize previously unidentified fungal species with latent or active capabilities for plastic decomposition. However, findings indicate that exposure to ultraviolet (UV) radiation remains a prerequisite for initiating plastic breakdown by *P. album*. Laboratory trials confirm that the fungus can only metabolize polyethylene (PE) that has undergone prior photodegradation. As noted by Vaksmaa, this constraint implies that fungal plastic degradation in marine environments is limited to debris that has floated near the ocean surface and received sufficient UV exposure.

Fig .2

Insights and Future Prospects in Marine Fungal Plastic Degradation

- While it has been previously established that ultraviolet (UV) radiation can mechanically degrade plastics, recent findings provide compelling evidence that UV exposure also enhances the biological degradation of plastics by marine fungi.
- Despite the capabilities of *Parengyodontium album* (*P. album*), it is unlikely to be effective in decomposing the entirety of oceanic plastic waste, as a significant portion of debris submerges to deeper oceanic layers before receiving sufficient UV irradiation. As such, *P. album* primarily acts on plastic that has remained at or near the ocean surface.

- Dr. Vaksmaa hypothesizes that other, yet unidentified, fungal species may inhabit the mesopelagic and bathypelagic zones and possess the enzymatic machinery necessary for plastic degradation under low-light conditions. These organisms may represent a largely untapped reservoir of biodegradative potential in marine ecosystems.
- The researchers suggest that *P. album* is likely one of many undiscovered marine fungi capable of breaking down complex carbon-based polymers such as polyethylene. As Vaksmaa notes, "Marine fungi possess the enzymatic capacity to decompose carbon-rich synthetic materials, and it is highly probable that numerous additional species—beyond the four currently identified—contribute significantly to the biodegradation of plastic in marine environments."
- Nonetheless, the underlying mechanisms and environmental dynamics governing plastic degradation in the ocean's deeper strata remain poorly understood and warrant extensive further investigation. [7]

Challenges and Directions for Future Research

- Although recent discoveries in microbial and enzymatic plastic degradation present significant promise, comprehensive research is still required to optimize the efficiency and scalability of these processes. Additionally, ethical and ecological considerations must be addressed to ensure that the deployment of such biological agents does not disrupt existing ecosystems or create unintended consequences.
- The degradative capacity of fungi, insects, and microorganisms is highly contingent upon specific environmental parameters, including temperature, humidity, oxygen levels, and the availability of essential nutrients. These factors influence both the metabolic activity of the organisms and the physicochemical properties of the plastics, thereby impacting the overall degradation process.

III. RESULTS

- The study focused on the marine fungal species *Parengyodontium album*, one of the few fungi currently identified with the capability to biodegrade polyethylene (PE)—a widely used and environmentally persistent synthetic polymer.
- The presence of ultraviolet (UV) light was determined to be a critical factor in facilitating plastic degradation. UV radiation not only induces the mechanical fragmentation of polyethylene but also enhances the biological accessibility of the polymer to fungal enzymatic activity.
- Degradation Limitations: The degradation capacity of *P. album* is constrained to polyethylene that has been exposed to sunlight. As such, the fungus predominantly acts on plastic debris that remains near the ocean surface, thereby limiting its potential efficacy in deeper marine zones.
- Degradation Rate: Under controlled laboratory conditions, *P. album* demonstrated the ability to mineralize UV-pretreated polyethylene at an approximate rate of 0.05% per day over a period of nine days. This rate highlights a gradual yet measurable capacity for fungal-driven plastic breakdown.
- Prospects for Further Exploration: Current research is expanding to determine whether other, still-undiscovered fungal species residing in the ocean's deeper layers also contribute to the degradation of plastic. These investigations aim to broaden the understanding of fungal biodiversity and its ecological role in marine plastic bioremediation.

IV. DISCUSSION

- While microbial plastic degradation offers a promising avenue for mitigating environmental pollution, it raises pertinent ecological concerns—particularly regarding the byproducts released during the biodegradation process. The metabolic waste excreted by plastic-degrading organisms, such as *Parengyodontium album*, may pose unforeseen risks to surrounding marine biota. It is crucial to investigate whether these degradation byproducts exert toxicological effects on other components of the marine ecosystem.

- Analytical techniques such as High-Performance Liquid Chromatography (HPLC) and various spectroscopic methods (e.g., UV-Vis, FTIR, and Mass Spectrometry) could be employed to characterize the chemical composition of both intermediate and final degradation products. These tools are essential in verifying the extent of polymer breakdown and in identifying potentially harmful compounds formed during the process.
- Another critical consideration is the environmental adaptability of these organisms. The enzymatic activity and plastic-degrading efficiency of fungi and other microorganisms are highly sensitive to external factors such as temperature, salinity, pH, and nutrient availability. When introduced into non-native environments, these organisms may exhibit reduced degradation efficiency or experience physiological stress. Such stress may manifest as altered metabolic pathways, suppressed enzyme production, or shifts in microbial community dynamics—all of which can influence the overall degradation process.
- Future research should prioritize comprehensive ecotoxicological assessments and environmental adaptability studies to evaluate the viability and safety of deploying plastic-degrading organisms in diverse ecosystems.

V. CONCLUSION

In summary, the findings affirm that *Parengyodontium album*, a marine-derived fungal species, exhibits the capability to biologically degrade polyethylene—one of the most pervasive plastics used in consumer goods such as packaging materials, grocery bags, and disposable bottles.

Although the discovery holds considerable promise for biotechnological applications in plastic waste mitigation, it is evident that further research is essential. Enhancing the degradation efficiency, ensuring ecological safety, and understanding the broader environmental implications remain critical priorities. The degradation efficacy of these fungi and other plastic-degrading microorganisms is highly dependent on specific environmental parameters, including temperature, ultraviolet exposure, nutrient availability, and the physicochemical nature of the polymer substrate.

Current investigations are increasingly focused on elucidating the molecular and cellular mechanisms underlying microbial plastic degradation, as well as exploring the feasibility of targeting a broader spectrum of synthetic polymers through enzymatic or microbial interventions.

It is important to recognize, however, that while this biological solution contributes to the broader fight against plastic pollution, it is **not a panacea**. The global plastic crisis necessitates a multifaceted approach, where microbial degradation technologies complement, but do not replace, systemic efforts toward reducing plastic production, improving recycling infrastructure, and promoting sustainable consumption patterns.

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VII. REFERENCE :

1. Biodegradation of polyethylene by the marine fungus *Parengyodontium album* , https://doi.org/10.1016/j.scitotenv.2024.172819.
2. https://www.reuters.com/business/environment/plastic-eating-fungi-could-be-glimmer-hope-cutting-ocean-pollution-2024-08-08/
3. Fungi degrading plastics: selection and evaluation of their activity *TEMPORITI, MARTA ELISABETTA ELEONORA*, ***2023-04-19***
4. Phylogenetic Distribution of Plastic-Degrading Microorganisms https://journals.asm.org/doi/full/10.1128/msystems.01112-20
5. Microbes of XVI century Arrases of Krakow Royal Castle https://www.sciencedirect.com/science/article/pii/S0944501320303530
6. Polyethylene degradation and assimilation by the marine yeast *Rhodotorula mucilaginos* https://pmc.ncbi.nlm.nih.gov/articles/PMC10330194/
7. https://www.packaginginsights.com/news/international-researchers-discover-plastic-eating-sea-fungus.html.
8. https://wjpsonline.com/index.php/wjps/article/view/1487 RP- HPLC method.
9. The world of plastic waste: A review https://www.sciencedirect.com/science/article/pii/S2772397624000042
10. *Parengyodontium album*, a frequently reported fungal species in the cultural heritage environment **https://doi.org/10.1016/j.fbr.2020.06.002**
11. Apinya T, Sombatsompop N, Prapagdee B (2015) Selection of a Pseudonocardia sp. RM423 that accelerates the biodegradation of poly (lactic) acid in submerged cultures and in soil microcosms. Int Biodeterior Biodegrad99:2330. https://doi.org/10.1016/j.ibiod.2015.01.001
12. Development of an Incubator System for Polyethylene plastic-eating Wax Worm in Tropical Weather Condition. https://ieeexplore.ieee.org/abstract/document/10109436
13. Photosynthetic microbial fuel cell with polybenzimidazole membrane: synergy between bacteria and algae for wastewater removal and biorefinery DOI:10.1016/j.heliyon.2018.e00560
14. Recent advances in microbial fuel cells (MFCs) and microbial electrolysis cells (MECs) for wastewater treatment, bioenergy and bioproducts https://doi.org/10.1002/jctb.4004
15. Anderson, S. (2014, December 15). The Plastic-Eating Fungi That Could Solve Our Garbage Problem. Retrieved February 26, 2016, from http://www.newsweek.com/ 2014/12/26/plastic-eating-fungi-could-solve-our-garbage-problem-291694.html
16. Akutsu, Y., T. Nakajima-Kambe, N. Nomura, and T. Nakahara. 1998. Purification and properties of a polyester-polyurethane degrading enzyme from Comamonas acidovorans TB-35. Appl. Environ. Microbial. 64:62–67.
17. Nakajima-Kambe, T., Y. Shigeno-Akutsu, N. Nomura, F. Onuma, and T. Nakahara. 1999. Microbial degradation of polyurethane, polyester polyurethanes, and polyether polyurethanes. Appl. Microbial. Biotechnology. 51:134– 140.
18. Moriyama, Y., Kimura, N., Inoue, R., and Kawaguchi, A. (1993). Examination of fungal deterioration on plasticized polyvinyl chloride by cryo-scanning electron microscopy. *Int. Biodeterior. Biodegrade.* 31, 231–239. doi: 10.1016/0964-8305(93)90008-P
19. Mueller, U. G., Gerardo, N. M., Aanen, D. K., Six, D. L., and Schultz, T. R. (2005). The evolution of agriculture in insects. *Annu. Rev. Ecol. Evol. Syst.* 36, 563–595. doi: 10.1146/annurev.ecolsys.36.102003.152626
20. Christophe MR. LeMoine, Harald C. Grove, Charlotte M. Smith, Bryan J. Cassone. A Very Hungry Caterpillar: Polyethylene Metabolism and Lipid Homeostasis in Larvae of the Greater Wax Moth

(Galleria mellonella). *Environmental Science & Technology* **2020**, *54* (22) , 14706-14715. https://doi.org/10.1021/acs.est.0c04386

21. Gloria Ifeoma Ujuagu, Onome Ejeromedoghene, Victor Enwemiwe, Chiamaka Linda Mgbechidinma, Ahmed Olalekan Omoniyi, Abiodun Oladipo, Jintu Gu. Exploring the toxicology, socio-ecological impacts and biodegradation of micro plastics in Africa: Potentials for resource conservation. *Toxicology Reports* **2025**, *14* ,101873. https://doi.org/10.1016/j.toxrep.2024.101873 .