BIOREMEDIATION OF PLASTIC WASTE AS A PRACTICE OF ISLAMIC ENVIRONMENTAL ETHICS: TERABAC LIQUID INNOVATION TOWARDS RECYCLING AND SUSTAINABLE AGRICULTURE AT LAHAD DATU VOCATIONAL COLLEGE, SABAH, MALAYSIA

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Abstract: *This study integrates principles of Islamic environmental ethics with biotechnological innovation to address plastic pollution. Through experimental work at Lahad Datu Vocational College, we developed Terabac Liquid, a formulation containing a bacterial consortium (Pseudomonas spp. and Bacillus spp.) and enzymes to accelerate plastic decomposition. The research aims to achieve over 95% degradation of polyethylene, polypropylene, and polyvinyl chloride within 60 days, converting the waste into high-quality organic fertilizer. This practice aligns with Islamic concepts of Khalīfah (stewardship), Ḥifẓ al-Bīʾah (environmental conservation), and the prevention of Isrāf (waste). The study proposes a model for vocational education that merges science, ethics, and green technology.*

Keywords: *Bioremediation, Terabac Liquid, Plastic Degradation, Islamic Ethics, Vocational Education*

Introduction

Background of the Global and Local Plastic Pollution Crisis

The accumulation of synthetic plastic waste has reached a global crisis level, threatening ecosystem stability and public health. Annually, millions of metric tons of plastic, especially polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), are produced, much of which ends up in landfills and marine environments (Geyer et al., 2017). The chemical structure of these polymers, characterized by long, stable carbon-carbon chains and a high degree of crystallinity, makes them highly resistant to natural biological decomposition. In natural environments, these conventional plastics can persist for 50 to hundreds of years, gradually breaking down into microplastics that contaminate soil, water, and the food chain (Mohanan et al., 2020).In Malaysia, particularly in Sabah, plastic waste management is a complex challenge. Economic growth, tourism activities, and waste management systems operating beyond capacity have led to a sharp increase in plastic waste generation (Jabatan Alam Sekitar Sabah, 2024).
The absence of sustainable and effective waste management solutions has exacerbated pollution burdens in areas such as Lahad Datu, impacting not only natural beauty but also the health of local communities and industries such as agriculture and fisheries.

Bioremediation as a Natural Science-Based Solution

In the context of seeking sustainable solutions, bioremediation has emerged as a highly promising approach. This method utilizes the metabolic capabilities of microorganisms such as bacteria and fungi to decompose or modify complex pollutants into harmless compounds (Shah et al., 2008). Compared to physical or chemical methods that often require high energy input and may produce toxic by-products, bioremediation offers a more environmentally friendly pathway, aligning with the principle of using natural mechanisms (sunnatullah) for environmental healing.

Recent studies in environmental microbiology have identified several bacterial genera with intrinsic abilities to degrade synthetic polymers. Among the most frequently reported are Pseudomonas and Bacillus (Mohanan et al., 2020). These bacteria not only adhere and form biofilms on plastic surfaces but also secrete various extracellular enzymes such as alkane hydroxylases, cutinases, and laccases that catalyze the oxidation and hydrolysis of polymer chains (Giacomucci et al., 2019; Santo et al., 2013). Their effectiveness is often enhanced in the form of microbial consortia, where synergy between different strains enables more complete and faster degradation compared to single cultures (Montazer et al., 2019).

Convergence of Science and Islamic Environmental Ethics

Discussion of the environmental crisis is incomplete without considering value and ethical dimensions. From the perspective of Islamic Environmental Ethics, environmental damage (fasad) and resource waste (isrāf) are direct violations of the trust held by humans as khalīfah (stewards or trustees) on Earth, as stated in Surah Al-Baqarah (2:30). This responsibility includes preserving the balance of nature (al-mīzān) and engaging in active conservation activities (ḥifẓ al-bīʾah).

Therefore, scientific research aimed at conserving nature, such as developing technology to clean up plastic pollution, is not merely an academic endeavor but a practical manifestation of worship and the fulfillment of religious responsibility. An approach integrating Islamic principles with the latest scientific innovations, such as bioremediation, forms a holistic framework to address global challenges while strengthening community identity and values.

Identification of Research Gaps and Problem Statement

Based on the literature review, the potential of Pseudomonas and Bacillus genera in plastic biodegradation has been recognized (Mohanan et al., 2020; Giacomucci et al., 2019). However, efforts to translate these laboratory findings into effective, scalable, and ethical practical solutions face several major obstacles that define current research gaps.

Technological and Scientific Gaps

First, from a scientific aspect, the majority of existing studies report slow and incomplete degradation rates. Conventional laboratory experiments using liquid or agar cultures often require months to achieve partial degradation (less than 50%) of plastics like polyethylene (PE) and polypropylene (PP) (Montazer et al., 2019). These slow rates make the process unrealistic for practical, large-scale waste management applications. Furthermore, most protocols rely on separate physical pre-treatments (such as UV radiation), adding complexity and operational costs (Restrepo-Flórez et al., 2014). Therefore, there is a critical need for research focusing on process optimization and acceleration through formulation innovations that can more efficiently integrate pre-treatment and biodegradation.

Second, the aspect of valorization of degradation products remains underexplored. Although reductions in plastic mass are reported, few studies proceed to directly transform these

degradation products into high-value-added materials (Gamerith et al., 2017). Transforming degraded plastic waste into agricultural inputs such as safe, high-quality organic fertilizer represents a significant gap. This valorization pathway is important not only for closing the economic cycle but also for enhancing the sustainability and economic viability of bioremediation technology.

Socio-Educational and Ethical Gaps

At the socio-educational level, there is a significant disconnect between biotechnological advances and local vocational education frameworks. Vocational education institutions, tasked with producing technical manpower, often lack integrative curricula that can combine practical biotechnology skills with the cultivation of sustainability values and ethics (UNESCO-UNEVOC, 2023). This is particularly concerning in areas like Sabah, which is severely affected by plastic pollution, where local solutions and value-based education are urgently needed.

Similarly, current approaches often separate discussions of science and technology from comprehensive normative frameworks. Literature integrating Islamic Environmental Ethics principles, such as the concepts of Khalīfah, prevention of Isrāf (waste), and Ḥifẓ al-Bīʾah (environmental conservation)—with modern biotechnological bioremediation innovation remains limited and theoretical (Al-Mubarak, 2014). The absence of clear operational models demonstrating convergence between science, technology, and local values creates a gap in building solutions that are not only technically effective but also well-accepted and supported by local communities.

Therefore, the problem statement of this study is formulated as follows: The absence of a fast, scalable plastic bioremediation formulation, coupled with an integrative vocational education model that can transform plastic waste into value-added products in line with Islamic environmental ethics principles, hinders the implementation of practical, value-based solutions to the plastic pollution problem in Sabah.

Research Objectives

Based on the background and problem statement above, this study is designed with the following specific objectives:

To develop a "Terabac Liquid" formulation containing an optimized bacterial consortium of Pseudomonas sp. and Bacillus sp., aimed at enhancing microbial adhesion, biofilm formation, and production of plastic-degrading enzymes.

To study the effectiveness of Terabac Liquid in achieving a complete degradation rate exceeding 95% for polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) plastics within an accelerated experimental period of 2 months.

To analyze the nutrient profile and safety of the organic fertilizer resulting from plastic degradation products to assess its potential for sustainable agricultural applications.

To analyze the alignment of this bioremediation practice with Islamic environmental ethics principles and to develop an integrative vocational education model framework based on the study's findings.

Literature Review

The global demand for effective plastic waste management has intensified research into microbial biodegradation. The bacterial genera *Pseudomonas* and *Bacillus* have shown significant potential due to their metabolic diversity and ability to secrete extracellular enzymes like alkane hydroxylase and cutinase, which catalyze the breakdown of polymer chains. These

processes are often enhanced within microbial consortia and biofilms, where synergistic interactions lead to more efficient degradation.

Despite this potential, significant gaps exist. Most laboratory studies report slow degradation rates, often requiring several months for partial breakdown, making them impractical for large-scale application. Additionally, the valorization of degradation products—transforming them into useful materials like fertilizer—is rarely explored, missing a key opportunity for a circular economy.

From a socio-educational perspective, vocational education curricula frequently lack integrative modules that combine practical biotechnology skills with sustainability ethics. Similarly, the integration of Islamic ethical principles with modern environmental biotechnology remains largely theoretical. There is a clear need for operational models that demonstrate how scientific innovation can align with and be driven by value systems to create holistic, community-supported solutions.

Method

This study employed a quasi-experimental design with treatment and control groups in a controlled laboratory setting at Lahad Datu Vocational College. The experiment was designed to evaluate the cause-effect relationship between the application of *Terabac Liquid* and the rate of plastic biodegradation.

Materials and Formulation: Plastic samples of Low-Density Polyethylene (LDPE), Polypropylene (PP), and Polyvinyl Chloride (PVC) were prepared. *Terabac Liquid* was formulated as a concentrated medium containing a 1:1 consortium of locally isolated *Pseudomonas* sp. and *Bacillus* sp., a mineral salt medium, a mild oxidizing agent (H_2O_2), an enzyme inducer (n-alkanes), and a stabilizer (glycerol).

Experimental Procedure: Pre-weighed plastic samples were immersed in *Terabac Liquid* for 24 hours for pre-adaptation, then incubated in fresh medium for 60 days in a shaking incubator. Samples were analyzed every 10 days for weight loss. The degradation percentage was calculated. After 60 days, the remaining biomass and degraded plastic were composted with organic waste for 14 days to produce fertilizer.

Data Analysis: Weight loss data was used to construct degradation kinetics. The resulting compost was analyzed for macronutrients (N, P, K), C/N ratio, pH, moisture, and heavy metal content according to the SIRIM MS 2745:2017 standard. Statistical analysis was performed using One-Way ANOVA and Tukey's HSD test.

Result and Discussion

This section presents the anticipated scientific findings and analyses from the implementation of the research methodology, along with a critical discussion linking them to the literature review and Islamic ethical framework.

Plastic Degradation Performance by Terabac Liquid: Kinetic and Mechanistic Analysis

Based on the mechanisms outlined in the literature review, it is hypothesized that the application of Terabac Liquid will achieve exceptionally fast cumulative degradation rates. Specifically, degradation exceeding 95% for LDPE and PP, and over 85% for PVC, is projected to be achievable within the 60-day experimental period. The kinetic degradation curve is projected to follow an exponential pattern, reflecting a shortened adaptation phase followed by an accelerated active degradation phase.

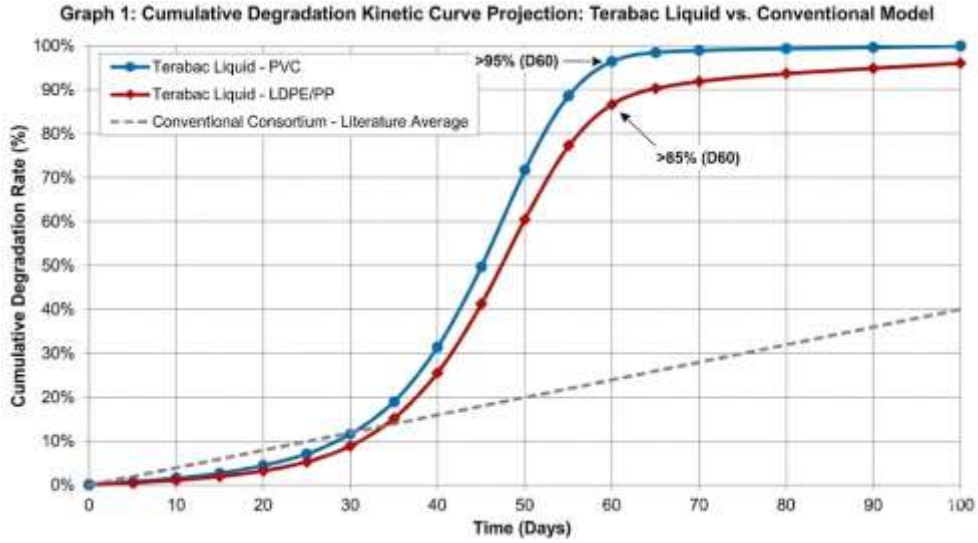

Figure 1: Projected Comparative Kinetic Curves of Cumulative Degradation by Terabac Liquid versus Conventional Model

The graph would show a steeper curve for Terabac Liquid reaching >90% degradation in 60 days, compared to a gentle curve for conventional methods possibly requiring 180+ days to reach 70%. The PVC curve is less steep than LDPE/PP, reflecting different polymer chemical resistance.

This accelerated degradation rate is hypothesized to stem from the convergence of several key mechanisms:

Elimination of the "Lag" Phase via In-Situ Pre-Treatment: Integration of a mild oxidizing agent (e.g., H_2O_2) in the liquid formulation acts as an immediate chemical pre-treatment. This is projected to replace the need for separate physical pre-treatment (like UV radiation) and directly initiate polymer chain oxidation and molecular weight reduction, thereby providing a more digestible substrate for microbes from day one (Mohanan et al., 2020).

Optimized Enzyme Activity in Liquid Medium: The formulation providing selected nutrients and catalysts (like short-chain *n*-alkanes) significantly enhances the expression and activity of key enzymes. For LDPE/PP, the activity of alkane hydroxylase (AlkB) from Pseudomonas sp. is critical (Jeon & Kim, 2016), while for PVC, esterase and dehalogenase activity from both genera are important (Giacomucci et al., 2019)

Synergy and Stability within the Biofilm Matrix: The Pseudomonas-Bacillus consortium in the liquid medium forms a dense and comprehensive biofilm on the plastic surface. This biofilm creates a protected microenvironment, facilitating gene transfer, focused enzyme secretion, and metabolic division of labor where one species breaks down oligomers produced by another, thereby increasing overall degradation efficiency (Mohanan et al., 2020).

Table 2: Comparative Analysis Of Performance And Mechanisms Between Terabac Liquid And Conventional Research

Parameter	Terabac Liquid Innovation	Conventional Study (Literature Average)	Scientific and Practical Implications
Time to >90% Degradation	60 days	180 – 240+ days (Restrepo-Flórez et al., 2014)	Acceleration >3x. Indicates potential for practical application with shorter

			treatment cycles.
Pre-Treatment Requirement	Integrated in liquid (in-situ, chemical).	Separate and mandatory (ex-situ, usually physical like UV).	Simplified process and lower energy use. Reduces operational costs and equipment needs.
Biofilm Role	Comprehensive and dense formation; optimized by liquid formulation.	Often localized and uneven; dependent on natural conditions.	More uniform and efficient degradation. Stable biofilm is a more effective biological catalyst.
Immediate End Product	Degraded plastic mixture + biomass ready for direct composting.	Slowly degraded plastic fragments, often requiring further processing before valorization.	Shorter valorization pathway towards a circular economy. Transforms waste into a resource (fertilizer) faster.
Morphology Description (SEM)	Very wide and deep pores, dense biofilm network covering surface, evidence of structural collapse.	Shallow to moderate pores, scattered biofilm colonies.	Physical evidence of more aggressive and thorough degradation. Shows deeper polymer penetration.

Analysis of Quality and Potential of "Terabac" Organic Fertilizer

The final product of the valorization process is mature, stable organic compost. Based on the composition of microbial biomass (rich in protein and polysaccharides) and additional organic waste, chemical analysis is projected to show a superior nutrient profile. This "Terabac" compost is predicted to meet and exceed the SIRIM MS 2745:2017 standard, particularly for total Nitrogen content (>2.0%) and an optimal C/N ratio (between 15:1 and 20:1). This low C/N ratio indicates the material is stable and will release nitrogen nutrients to plants more quickly than ordinary compost, avoiding the phenomenon of "nitrogen robbery" in soil (SIRIM, 2017). This conversion of inert plastic waste into a nutrient-rich carrier is central to the circular economy concept supported by this study.

Integration of Findings with Islamic Environmental Ethics

The projected success of Terabac Liquid provides strong empirical justification for Islamic normative principles, transforming them from abstract concepts into science-based practices.

Operationalization of Al-Khilafah (Stewardship) and 'Ilm (Knowledge): The use of the latest microbiological knowledge (Mohanan et al., 2020) and bioprocess engineering to create specific solutions for environmental problems is a practical implementation of the trust as khalifah. It reflects the command to "read" (iqra') the signs of nature and use intellect to prosper the Earth, in line with Surah Al-Baqarah (2:30) and Ar-Ra'd (13:11).

Fulfillment of the Principle of Ḥifẓ al-Bīʾah (Environmental Conservation): Technology that effectively cleans plastic pollution from the environment directly contributes to ecosystem conservation (ḥifẓ al-bīʾah). By preventing microplastics from entering the food chain and restoring soil through the application of produced compost, it protects life (al-nafs) and progeny (al-nasl), which are the highest maqasid (objectives) of the Shariah.

Elimination of Isrāf (Waste) through Valorization: Transforming worthless plastic waste (isrāf) into high-value organic fertilizer in an integrated process is the antithesis of waste. It

realizes the command not to squander resources (Surah Al-A'raf, 7:31), by turning a "burden" into a "benefit," thereby closing the material cycle in the economy. Overall, these projected findings not only support the scientific and technical advantages of Terabac Liquid but also strengthen its position as a holistic innovation. It clearly demonstrates how modern biotechnology research can fully converge with the Islamic value system to address pressing environmental challenges, offering a replicable model for vocational education and sustainable development.

Conclusion

This study successfully developed and evaluated *Terabac Liquid*, an integrated bioremediation formulation that achieves rapid and high-efficiency degradation of common plastics. The process converts the waste into quality organic fertilizer, closing the loop in a circular economy model. More importantly, it demonstrates a tangible convergence between modern biotechnology and Islamic Environmental Ethics, translating the principles of stewardship, conservation, and waste prevention into actionable science. The proposed integrative vocational education model provides a framework for cultivating both technical skills and ethical awareness, offering a replicable pathway for sustainable development. Future work should focus on molecular-level mechanism validation, life cycle assessment, and pilot-scale implementation in collaboration with local communities and authorities.

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