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Biodegradation of Polystyrene Waste using Mealworm (*Tenebrio molitor*) Larvae as a Sustainable Waste Management Approach

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Abstract

Styrofoam is widely used for packaging food, beverages, and electronic goods, yet it is typically discarded after a single use, contributing to persistent environmental pollution. Conventional waste management methods for Styrofoam are limited by high costs and environmental risks, prompting the exploration of biological degradation as a sustainable alternative. This study investigates the potential of *Tenebrio molitor* larvae as biodegradation agents for Styrofoam under controlled laboratory conditions. A total of 150 larvae were cultivated in three treatments - Styrofoam feed, natural feed, and no feed - for 30 days. Parameters measured included larval viability, weight change, and FTIR-based chemical analysis of larval biomass. Results showed that larvae fed with Styrofoam exhibited the highest viability (78%) compared to those receiving natural feed (72%) and no feed (54%). FTIR spectra indicated no detectable polystyrene-derived functional groups in larval tissues, suggesting that observed degradation may be primarily mechanical or confined to the gut, with transformation products likely excreted in frass. These findings demonstrate that *T. molitor* can survive on Styrofoam alone and potentially contribute to its physical breakdown, although chemical mineralization remains inconclusive.

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INTRODUCTION

Styrofoam, scientifically known as polystyrene (PS), is a synthetic aromatic polymer widely employed in diverse applications, including food packaging, electronic device casings, and building materials. Its desirable properties, lightweight structure, water resistance, and high thermal insulation have driven extensive industrial use (Hadiyanto et al., 2021). However, these same properties contribute to its persistence in the environment. Due to its high molecular stability and hydrophobicity, PS can take several centuries to degrade naturally, thereby contributing to significant environmental pollution. Accumulated Styrofoam in terrestrial and marine ecosystems poses severe threats to wildlife through ingestion, entanglement, and habitat degradation (Phelan et al., 2020).

Conventional management approaches, including mechanical recycling and incineration, have been implemented with varying degrees of success (Choi et al., 2022). Nonetheless, these methods face limitations related to economic feasibility, process efficiency, and environmental safety. In particular, incineration often releases greenhouse gases and hazardous air pollutants such as dioxins and furans, exacerbating climate change and public health risks (Campanale et al., 2020; Verma et al., 2016). As a result, there is growing interest in developing alternative, environmentally friendly, and cost-effective technologies for Styrofoam degradation.

One promising avenue involves the application of biological agents capable of polymer biodegradation. *T. molitor* (mealworm) larvae have emerged as a potential solution due to their ability to consume and fragment PS (Jiang et al., 2021). Recent research suggests that their gut microbiota plays a critical role in metabolizing polystyrene into simpler compounds, including carbon dioxide, biomass, and potentially biodegradable intermediates (Bożek et al., n.d.; Park et al., 2023). These findings suggest that mealworm-assisted degradation could be integrated into circular waste management systems, offering a more sustainable and less hazardous alternative to conventional methods (Zahrah et al., 2024).

A promising approach that has gained attention in recent years is the use of *T. molitor* larvae as biological agents for Styrofoam degradation. Previous studies have demonstrated that *T. molitor* can ingest PS and, through the action of gut-associated microorganisms, convert portions of the polymer into carbon dioxide and larval biomass (Bożek et al., n.d.; Jiang et al., 2021; Park et al., 2023).

Despite these advances, several critical research gaps remain. First, the chemical degradation mechanism is not yet fully understood; many studies focus on mass loss or surface morphology changes without standardized, quantitative spectral analyses. Second, most research employs pristine PS, whereas commercial Styrofoam—especially in Indonesia—often contains additives such as dyes, plasticizers, and flame retardants that may influence degradation pathways and product composition. Third, the fate of degradation products remains unclear, particularly the proportion transformed into low-molecular-weight compounds, assimilated into biomass, released as CO_2, or persisting as potentially toxic residues (frass). Finally, there is a lack of studies conducted under tropical environmental conditions using reproducible and standardized FTIR-based metrics, which limits the applicability of existing findings to local waste management contexts (Nukmal et al., 2018).

This study addresses these gaps by focusing on the FTIR-based mechanistic elucidation of Styrofoam degradation by *T. molitor* using consumer-grade materials commonly found in Indonesia. Specifically, it employs a time-resolved FTIR protocol with baseline correction and band deconvolution to detect structural changes in aromatic C–H, C=C bonds, and the emergence of carbonyl and hydroxyl functional groups. Quantitative spectral indices such as the carbonyl index and aromatic ring index are calculated to provide standardized measures of chemical transformation. By generating high-resolution, context-specific chemical evidence, this research aims to advance the understanding of the degradation pathway of Styrofoam by *T. molitor* and evaluate its potential as an environmentally sustainable waste management strategy in Indonesia (Sun et al., 2022).

However, although it has been found that *T. molitor* can degrade Styrofoam, the chemical mechanism of this process is not fully understood. One of the analytical tools that can be used to understand these chemical changes is Fourier Transform Infrared Spectroscopy (FTIR). FTIR can identify changes in the chemical structure of the material by detecting molecular vibrations at infrared frequencies, thus providing information about changes in chemical bonds in the material undergoing degradation (Hadiyanto et al., 2021). Through the FTIR technique, changes in the chemical structure of Styrofoam before and after being digested by Mealworm can be identified. In this way, the chemical degradation that occurs during the biodegradation process can be analyzed in more detail. The data obtained from FTIR are expected to provide concrete evidence regarding the ability of *T. molitor* to degrade styrofoam (Nukmal et al., 2018).

Based on this background, the purpose of this study is to explore the potential of *T. molitor* in degrading styrofoam and to use FTIR as an analytical method to understand the chemical changes that occur during the degradation process. Through this study, it is expected that an effective and environmentally friendly biodegradation solution can be found to overcome the problem of Styrofoam waste.

METHOD

Materials

The study utilized *T. molitor* larvae (n = 150; mean initial weight: 0.15 ± 0.02 g per larva) obtained from local bird feed suppliers in Sekaran, Semarang City, Indonesia. The experiment was conducted at the Science and Environment Laboratory, Faculty of Mathematics and Natural Sciences (FMIPA), Universitas Negeri Semarang (UNNES), over a two-month period. The primary materials included commercial Styrofoam (polystyrene), natural feed components (wheat bran, chicken pellets, and jipang—a traditional puffed rice snack), glass jars (2 L capacity), and standard laboratory tools for weighing, drying, and sample preparation. The Styrofoam used was consumer-grade food packaging waste, cut into uniform blocks of 500 g each prior to use.

Experimental Design

A completely randomized design (CRD) was employed with three treatments, each replicated once in separate glass jars containing 50 larvae:

Treatment A: *T. molitor* without feed (starvation control)

Treatment B: *T. molitor* with natural feed provided once every two days

Treatment C: *T. molitor* with Styrofoam feed only

The larvae were maintained under ambient laboratory conditions (temperature: 27 ± 2 °C; relative humidity: 70 ± 5%) for a duration of 30 days. The jars were covered with fine mesh to allow ventilation and prevent larval escape. No additional moisture was provided to avoid microbial contamination.

Feeding and Maintenance

For Treatment B, natural feed was weighed and supplied every two days in portions equivalent to 5% of the total larval biomass. For Treatment C, Styrofoam blocks were placed directly into the jars and replaced if fully consumed or excessively fragmented. Treatment A larvae received no feed to serve as a starvation control. Residual feed and frass were removed weekly to prevent mold growth.

Data Collection

Data collection focused on:

Larval growth – Wet weight was recorded at the beginning and end of the experiment using an analytical balance (±0.001 g precision). Dry weight was obtained after oven-drying larvae at 50 °C for 24 h. Larval viability – Survival rate (%) was calculated based on the number of living larvae at the end of the study. Styrofoam mass loss – The mass of Styrofoam before and after feeding was measured to determine the degradation percentage.

Chemical analysis – Post-experiment larvae from each treatment were oven-dried, ground into powder, and analyzed using Fourier Transform Infrared Spectroscopy (FTIR) at the Physics Laboratory, FMIPA UNNES, to detect chemical bond changes in degraded Styrofoam.

Data analysis

Data analysis was conducted in two stages. First, descriptive statistics (mean ± standard deviation) were calculated for each parameter. Second, inferential statistical tests were applied to assess differences between treatment groups. FTIR spectral data were further analyzed by calculating functional group indices (e.g., carbonyl index, aromatic ring index) and comparing them statistically across treatments. All statistical analyses were performed using IBM SPSS Statistics 29, while graphical visualizations were produced using OriginPro 2024b.

RESULT AND DISCUSSION

Viability of Mealworms

Viability of Mealworms. Viability is the ability of an organism to survive, grow, and develop under certain conditions. Viability is used to describe the level of survival of an organism in a certain environment or treatment. Viability also includes the ability of individuals to grow normally, reproduce, and adapt to environmental changes. The viability of Mealworms is presented in the following Figure 1 below.

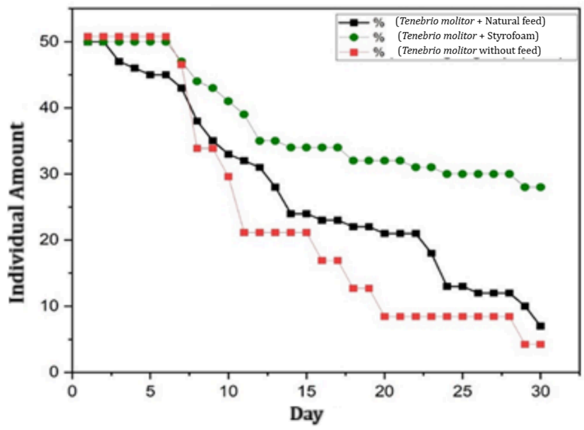

Figure 1. Viability of Mealworms

Based on the observation results, the highest viability of Mealworms was given the Styrofoam treatment. Mealworms that were not given feed treatment were the lowest. Mealworms given Styrofoam tended to show a decrease in viability in the long term. Although they could survive for some time by consuming Styrofoam, their growth and development slowed (body size shrinkage occurred). The mortality rate of Mealworms given Styrofoam was lower when compared to *T. molitor* given natural feed and without feed.

Figure 2. Mealworms after treatment: a) natural feed, b) btyrofoam, c) without feed

Styrofoam Degradation

The Styrofoam given as a treatment was seen to have holes made by Mealworms (Figure 3)

Figure 3. Styrofoam with holes due to being eaten by mealworms, and the condition of the styrofoam after 30 days of treatment

FTIR Test Results

Mealworms, after being treated for 30 days, were dried in an oven at a temperature of 50°C for 24 hours and then ground with a mortar pestle into biomass that was tested by FTIR. The results of the FTIR test are presented in the following image:

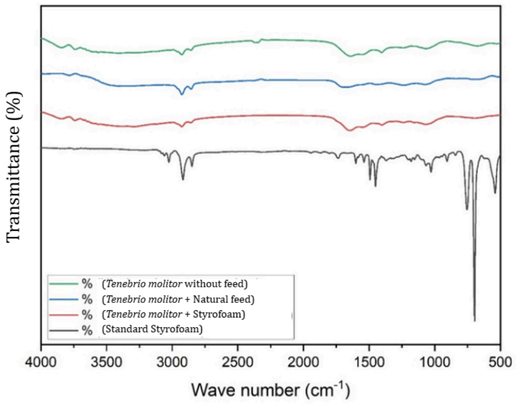

Figure 4. FTIR test results

Discussion

Mealworms (*T. molitor* larvae) are widely recognized as a high-protein food source for reptiles, birds, and fish, and more recently, they have attracted attention for their ability to consume recalcitrant polymers such as polystyrene (Nukmal et al., 2018). In the present study, an unexpected observation was that mealworms fed exclusively with Styrofoam exhibited the highest survival rate (78%), exceeding that of larvae given natural feed or deprived of feed. This contrasts with the general assumption that polystyrene lacks nutritional value to sustain larval growth (Y. Yang et al., 2020). Similar to our results, Peng et al. (2019) reported that *T. molitor* could survive for over 40 days on a polystyrene-only diet, albeit with reduced growth compared to those on nutrient-rich feed.

Interestingly, in our experiment, larvae in the Styrofoam treatment displayed morphological changes such as darker coloration and accelerated molting patterns, consistent with "premature aging" reported by (Y. Yang et al., 2020). This may indicate physiological stress, possibly due to an imbalanced nutrient profile, even though mortality was lower. The low mortality may be explained by the behavioral and habitat benefits of Styrofoam. Our observations of larvae chewing polystyrene to form interconnected tunnels mirror findings by Peña-Pascagaza et al. (2020), where polystyrene structures provided shelter, reduced desiccation stress, and potentially improved survival despite limited nutrition. The chewing behavior observed in morning and evening hours aligns with the crepuscular feeding activity patterns of *T. molitor* (Rumbos & Athanassiou, 2021).

From an environmental management perspective, the potential application of mealworm-mediated Styrofoam degradation in Indonesia merits careful consideration. In principle, this method could provide a low-energy, low-technology solution for reducing Styrofoam waste, especially in rural or island communities where formal waste management infrastructure is limited. The main advantages include minimal equipment requirements, the possibility of using locally sourced larvae, and the potential by-product of frass, which has been explored as a soil amendment (Kamaludin et al., 2025). However, there are constraints. First, the rate of degradation is slow: (Kamaludin et al., 2025)estimated that 100 mealworms degrade only ~35 mg of polystyrene per day, meaning that scaling to municipal waste volumes would require large populations, specialized housing, and sustained maintenance. Second, there are uncertainties about the safety of frass, as it may contain microplastic fragments or partially oxidized compounds (Nakatani et al., 2024), necessitating additional post-treatment before environmental release. Third, the economic viability depends on balancing operational costs (larval rearing, housing, labor) with waste reduction benefits, which may only be feasible at a community scale rather than in centralized facilities (Yang et al., 2021).

A notable finding of our study was that FTIR analysis did not detect polystyrene-derived compounds in the larval biomass. While this could suggest that larvae primarily shred Styrofoam for habitat rather than chemically digesting it, previous studies have documented partial depolymerization and oxidation of polystyrene in the gut (Putra & Ma'rufah, 2022; Y. Yang et al., 2020). The absence of detectable polystyrene signatures in our samples could be due to limitations in sensitivity, the relatively short experimental duration (30 days), or the analytical focus on larval tissues rather than frass. Dimassi et al. (2022) emphasized that most of the chemical transformation products appear in frass, suggesting that exclusive analysis of larval bodies may underestimate degradation activity.

Limitations and future work. This study has several limitations. First, the experimental duration and sample size were relatively small, limiting our ability to capture long-term degradation trends. Second, only larval biomass was analyzed via FTIR, potentially overlooking degradation products in frass. Third, no quantitative measurement of polystyrene mass loss was linked directly to chemical bond scission, leaving the mechanistic pathway unresolved. For future research, we recommend: (i) incorporating time-resolved mass balance analyses of both larvae and frass; (ii) conducting GC–MS or NMR to detect low-molecular-weight oxidation products; (iii) testing degradation efficiency under tropical outdoor conditions to simulate real waste management scenarios; and (iv) evaluating frass toxicity before proposing large-scale use. These recommendations align with best practices in recent biodegradation studies (Boschi et al., 2024)

Overall, our results suggest that Styrofoam can sustain mealworm viability and potentially contribute to localized waste reduction. The feasibility of this method as a scalable solution in Indonesia will depend on overcoming challenges in degradation rate, safety verification, and economic cost–benefit balance.

CONCLUSION

The findings of this study suggest that *T. molitor* larvae could serve as a practical, low-cost solution for managing Styrofoam waste in Indonesia. By surviving and mechanically processing polystyrene, mealworms offer an environmentally friendly alternative to conventional methods such as incineration or mechanical recycling, which are often energy-intensive and produce greenhouse gas emissions. Implementing mealworm-assisted degradation at a community or industrial scale could reduce Styrofoam accumulation in landfills and coastal areas, while generating larval biomass and frass that may have secondary applications, such as animal feed or soil amendment. However, a successful application requires careful optimization of larval density, exposure time, and waste collection logistics to achieve meaningful reductions in Styrofoam volume. This approach provides a promising avenue for integrating circular economy principles into waste management strategies in Indonesia, aligning environmental sustainability with practical feasibility.

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