



Research Article

## Optimizing *Tenebrio Molitor* Feeding Strategy to Induce Physical Degradation of Tires: A Novel Approach for Sustainable Waste Management

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### Abstract

Due to the increased usage of tires, the accumulation of worn tires has become a significant environmental concern and necessitates environmentally friendly waste management strategies. Conventional methods, such as tire incineration or improper disposal, contribute to environmental degradation. It is reported that organisms, such as *Tenebrio molitor* larvae, can degrade a wide range of polymers. This study explores the promising potential of *Tenebrio molitor* larvae in addressing this concern. Through a series of experiments, *Tenebrio molitor* larvae were fed with cut-worn tires to facilitate degradation. The larvae exhibited remarkable capabilities, surviving and thriving on tires as a sole carbon source for 24 days, with a maximum tire consumption of 0.2519 g observed. A significant 58.27% increase in larval mass was observed when a diet comprising 25% tires and 75% oat brans was provided. Analytical techniques, including FTIR, TGA, and SEM, successfully demonstrated the larvae's efficient consumption of tire materials. These findings highlight the potential of *Tenebrio molitor* larvae as an eco-friendly solution for tire disposal, offering insights into sustainable waste management practices.

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### Introduction

Rubber is one of the raw materials that is often used in various fields. According to the International Rubber Study Group, in 2017–2025, it can be estimated that the total world rubber consumption will increase by an average of 2.8% per year [1]. One field that often uses rubber as a raw material is the automotive field, where rubber is usually used to make tires. The matrix commonly used in tire components is typically made from synthetic rubber in styrene butadiene rubber (SBR) or a mixture of natural rubber with SBR [2]. The rubber used for tires usually goes through a vulcanization process first, in which the rubber can undergo a cross-linking reaction. The cross-linking structure formed in

rubber can make the rubber more thermally stable and insoluble, so the rubber will be more challenging to recycle [3].

The disposal of waste tires has long been an environmental challenge. The difficulty in recycling these rubber-containing tires has led to their accumulation in landfills, incineration, or inadequate recycling, all of which have detrimental effects on the environment and public health [4]. The urgency of this issue is highlighted by the projection that waste tire disposal could reach 1,200 million units by 2030, up from approximately 1,000 million, if current trends persist [4–5]. This escalating situation demands an eco-friendly approach to waste tire management.

The disposal of waste tires poses a significant environmental challenge. Due to the composition of rubber, recycling tires is rugged. End-of-life tires (ELTs) are often left inadequately in landfills, incinerated, or recycled. Such mismanagement leads to environmental damage, adversely affecting wildlife and human health [4]. Annually, a substantial quantity of tires, approximately 1,000 million, are discarded into the environment. Projections indicate that by 2030, this number could escalate to 1,200 million if current trends persist [4–5]. Given the increasing accumulation of waste tires, there is an urgent need for an environmentally sustainable disposal method to prevent further environmental degradation.

An environmentally friendly method of waste tire disposal can be done with the help of organisms. Organisms such as *Tenebrio molitor* larvae have been known to degrade various polymers. *Tenebrio molitor* larvae are usually used commercially as feed for livestock or pets such as birds, reptiles, amphibians, and small mammals. They can also be used as bait when fishing and have the potential for sustainable alternatives such as food protein to meet human needs [6–8]. *Tenebrio molitor* larvae are also known to be able to consume various kinds of waste or organic materials [9]. Previously, it has been reported that *Tenebrio molitor* larvae can degrade a mixture of polyethylene and polystyrene foam [10]. Other studies also found that *Tenebrio molitor* larvae can depolymerize and biodegrade PVC, where the larvae can survive for five weeks when given PVC as the only food with a survival rate of 80% [8]. *Tenebrio molitor* larvae can also survive for three weeks when given vulcanized SBR and tire as the sole carbon source, where the tire left by the larvae has a lower degree of cross-linking [11]. Polypropylene polymers were also shown to be degradable by *Tenebrio molitor* larvae through microbe-dependent depolymerization in the larval gut, where depolymerization and biodegradation rates and survival rates in polypropylene biodegradation in this study were shown to be relatively high [12]. Although it is evident that the larvae are able to degrade vulcanized styrene butadiene rubber, a similar type of rubber as vehicle tire as used in this study, the rate of consumption and survivability of the larvae on rubber feed are unknown. This study aims to explore strategy to make *Tenebrio molitor* larvae adapts to the tire rubber feed and confirms the details of larvae capability to biodegrade tire waste.

## Materials and method

### 1) Materials

The primary materials used in this research are tires and oat bran. The tires used were tire inner tubes produced by PT Industri Karet Deli (Medan, Indonesia), with brand

name swallow®. Oat bran, serving as a control diet, was selected based on its established use as *Tenebrio molitor* feed, as in the study by Riaz et al. [7]. The oat bran used is Quaker® produced by Altratec Sdn. Bhd. (Klang, Malaysia). Oat bran contains complex carbohydrates, fiber, vitamins, and minerals required for larvae normal growth. *Tenebrio molitor* larvae used in this study were purchased from local markets in Depok, West Java, Indonesia. All larvae were subjected to a 96-hour starvation period before the experiment to empty their stomachs. Tires and oat bran were stored at room temperature, and fresh vegetables like potatoes were provided as additional nutrient sources and moisture during the larvae-rearing period [7].

## Method

### 1) Tire biodegradation

Tires were cut into irregular cubes of 1–2 cm<sup>2</sup> with 1 mm thickness. In each variation, 100 larvae were placed in an incubator to determine the rate of tire consumption and biodegradation by larvae. The incubators used were food-grade storage containers made from polypropylene plastic. During the larval rearing time, all incubators were kept at room temperature 25°C.

We are utilizing different compositions of feeds to examine larvae survivability. The feeds consist of oats and cutted tires which together weight 30% of total larvae body weight. We use 5 kinds of composition labeled as 0% oat, 25% oat, 50% oat, 75% oat, and 100% oat. 0% oat feed means that the feed consists of cutted tires without oat, the weight of tires that were used are 30% of total weight of 100 larvae in the incubator. 25% oat means that the feed contains oat and tires that together weights 30% of total weight of 100 larvae in the incubator, and that 25% (weight) of the feed consists of oats. The same scenario applies to 50% oat and 75% oat. 100% oat is used as negative control, consisting of oats only as the larvae food. However, larvae need water source in their meals, since oats have low water content we gave raw potato cuts every week, potatoes were given as much as 50% of the larval weight in each variation. Every  $\pm 7$  days, the leftover food are weighed and the new feed (tire and oat mixture, tire only, or oats only) are added totalling up to 30% of live larvae body weight. Dead larvae are immediately separated from the population to prevent them from being consumed by other larvae. The survival rate of *Tenebrio molitor* larvae can be determined by counting the number of the dead every  $\pm 3$  days. The mass of *Tenebrio molitor* larvae can be determined by calculating the mass of larvae that have been separated from the feed and feces. The tire consumption rate can be calculated by adding the mass of tires consumed every  $\pm 3$  days to the mass consumed

on the previous day. The specific rate of tire consumption was calculated based on the mass of tires consumed per larval weight per day ( $\text{mg tire} \cdot \text{g larvae}^{-1} \text{ day}^{-1}$ ) as previously used by Yang et al (2021) [12].

## 2) Evaluation of biodegradation by *Tenebrio molitor*

Various analytical instruments were used to evaluate the degradation ability of *Tenebrio molitor* in degrading tires. Fourier Transform Infrared Spectroscopy (FTIR) was performed to evaluate the changes in the functional groups of the tire before and after degradation using the iS5 Thermo Fischer model spectrophotometer. This FTIR tool was measured using the FTIR ATR (attenuated total reflectance) method. The sample was cleaned using a cleaning liquid called Isopropyl alcohol (IPA), ethanol. Then, the FTIR spectrum of the sample was recorded at a scanning range of  $4,000 - 650 \text{ cm}^{-1}$ , a resolution of  $8 \text{ cm}^{-1}$ , and a scanning time of 16 sec]. This test was conducted based on ASTM E1252–13 standard. A Scanning Electron Microscope (SEM) was also performed to evaluate the changes in the morphological structure of the tire following the degradation. SEM was conducted using Zeiss 5.00 kV with a magnification of 500-1,000x. Thermogravimetric Analysis (TGA) allows us to determine changes in the mass of a material as a function of time and temperature [11]. TGA is performed with a device called a thermogravimetric analyzer. TGA was conducted by heating samples from  $25^\circ\text{C}$  to  $750^\circ\text{C}$  with a heating rate of  $10^\circ\text{C}/\text{min}$ .

## 3) Statistical analysis

Experimental results were analyzed using MS. Excel and IBM Statistical Program for Social Science (SPSS) 26. The statistical analysis was determined by t-test and one-way Analysis of variance (ANOVA). Three independent biological replications of the experiment were performed.

## Results and discussions

### 1) Tire degradation test

*Tenebrio molitor* larvae have been demonstrated to consume and degrade tires effectively. During a 24-day observation period, the larvae, when fed various tire-containing diets, exhibited an increase in weight. The most significant weight gain, amounting to 58.27%, was observed in the 75%-OB variation. For the 25%-OB and 50%-OB variations, the larvae's weight gains were 32.42% and 23.87%, respectively. These results indicate that oat bran, a feed component, substantially contributes to larval weight increase. Conversely, as the amount of tire in the diet increased, the growth of larvae weight slowed. This situation suggests that tires, or SBR, possess limited nutritional value and are inadequate as a sole food source.

Figure 1 illustrates the larval mass gain across three types of feed. The observed non-constant curve trend is attributed to intermittent decreases in larval mass over several days. These fluctuations in mass, coupled with only slight increases in weight, may indicate the larvae's unmet nutritional needs. While SBR contains elements like carbon, oxygen, hydrogen, nitrogen, and carboxylate, *Tenebrio molitor* larvae require a range of nutrients, including amino acids, sodium, nitrogen, phosphorus, potassium, and trace elements, for sustained survival and growth [12].

The observed decrease in *Tenebrio molitor* larval mass may be attributed to excretion, which can reduce overall mass, particularly when food supplies are depleted, as depicted in Figure 2. Larvae that metamorphose into pupae are counted as deceased for this study, as the focus is solely on larvae for degradation processes. Dead larvae are immediately discarded to prevent cannibalism [12]. Larval mortality before the end of the observation period may result from insufficient oxygen, especially in cases where larvae cluster in a single area without even distribution, thereby increasing the mortality rate due to unmet oxygen requirements [13].

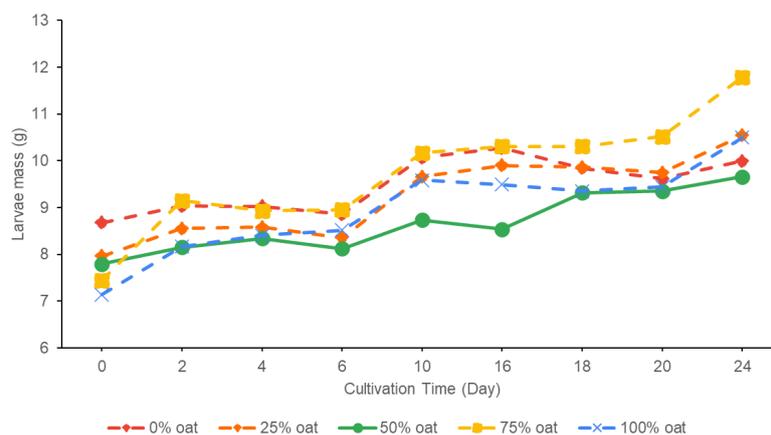
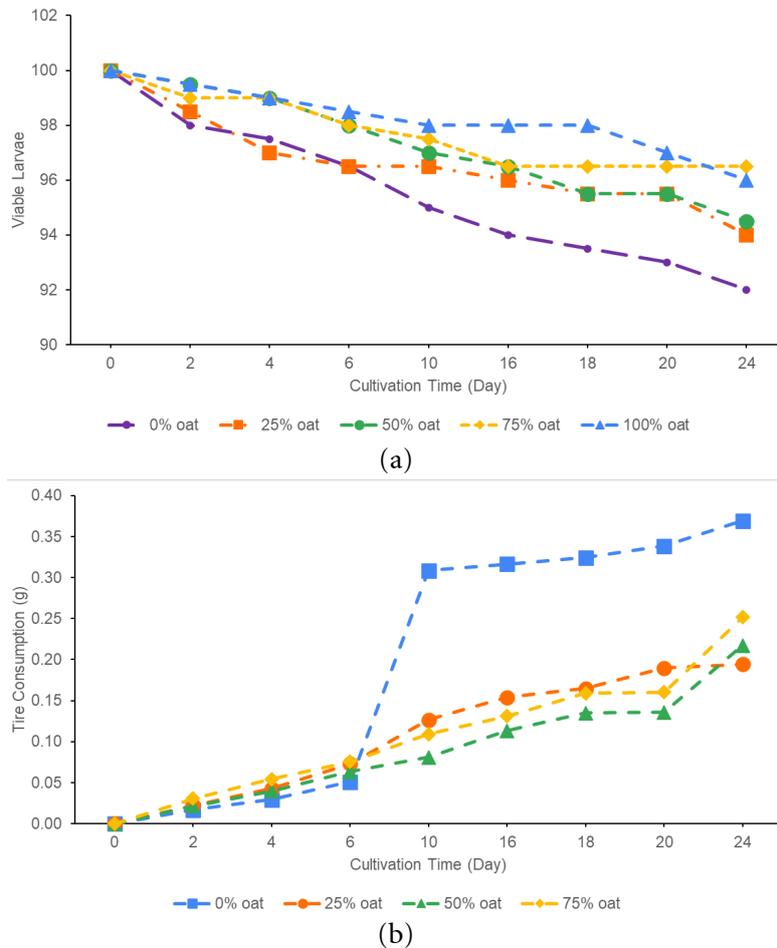


Figure 1 Mass change of larvae based on feeding strategy.



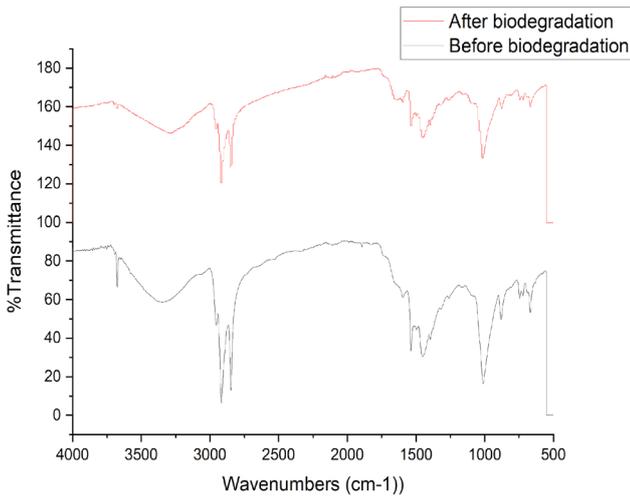
**Figure 2** The number of survival larvae and amount of tire consumption according to various feeding strategy.

When *Tenebrio molitor* larvae are exclusively fed tires, increased tire consumption is observed during the study period. The thinly cutted tires that are in the larvae cage were removed, weighted, and compared its weight with the original weight. The highest tire consumption was observed in the 0%-OB group, with 0.3695 g consumed over 24 days of cultivation. The second-highest consumption occurred in the 75%-OB group, where 0.2519 g were consumed and the specific rate of tire consumption reached 33.83 mg tire·g larvae<sup>-1</sup> day<sup>-1</sup>. These values reflect the larvae's daily tire consumption capacity [12]. Figure 2(a) shows that the highest larval survival count was 97 in the 75%-OB variation, while the lowest was 92 in the 0%-OB variation. The results suggest that higher tire content in the diet increases mortality rates compared to diets with more oat bran. High mortality of larvae was likely induced due to insufficient energy derived from the tires, leading to increased cannibalism and higher mortality rates in the larval population [12]. It is evident that larvae cannot obtain enough nutrients from tire feed alone. Together,

appropriate strategy is crucial for helping larvae adapt to new, non-food material feeds.

## 2) FTIR spectroscopy analysis

The FTIR analysis of waste tires, both before and after exposure to *Tenebrio molitor* larvae, as shown in Figure 3, reveals significant changes in chemical composition. Initially, the waste tires displayed a broad absorption band at 3343.58 cm<sup>-1</sup> associated with OH stretching in regular polymers. OH stretching is degraded by *Tenebrio molitor* which is characterized by the disappearance of the peak graph at wave 3,750 cm<sup>-1</sup>. Additionally, narrow absorption bands at 2,954.71 cm<sup>-1</sup> and 2847.19 cm<sup>-1</sup> indicated C-H stretching on CH<sub>3</sub> and CH<sub>2</sub>, while bands at 1,594.76 cm<sup>-1</sup> and 1,452.50 cm<sup>-1</sup> represented double bonds (C=C-C stretching), with nitro compounds at 1,536.76 cm<sup>-1</sup> in the aromatic ring framework. OH bending attributed to carboxylates at 1,396.03 cm<sup>-1</sup>, cyclohexane at 1012.02 cm<sup>-1</sup>, 1,2-substituted (ortho) C-H benzene group at 745.01 cm<sup>-1</sup>, and alkyne group bending at 667.87 cm<sup>-1</sup>, with C-O-O- stretching at 880.83 cm<sup>-1</sup> were also observed [11, 14].



**Figure 3** FTIR absorption bands of tires before and after contact with larvae.

Following exposure to *Tenebrio molitor* larvae for 24 days, notable changes were observed in the FTIR spectrum of the tires exposed to larvae. The OH stretching band slightly shifted from  $3,343.58\text{ cm}^{-1}$  to  $3,286.84\text{ cm}^{-1}$ , indicative of interactions with the larvae. Similarly, alterations occurred in C-H stretching bands at  $2,954.50\text{ cm}^{-1}$  and  $2,847.10\text{ cm}^{-1}$ , along with bands for double bonds (C=C-C stretching) and nitro compounds in the aromatic ring framework. The OH bending band at  $1,395.30\text{ cm}^{-1}$ , cyclohexane compound at  $1,013.36\text{ cm}^{-1}$ , benzene group at  $743.11\text{ cm}^{-1}$ , and alkyne group bending at  $666.20\text{ cm}^{-1}$  also displayed changes in post-larval exposure. Notably, the shifts in wavelength and changes in intensity of absorption bands linked to OH groups, carboxylates, C-H stretching, C=C-C stretching, and C-O-O- stretching demonstrate the weakening and possible breakdown of chemical bonds within the polymers post-degradation. These significant alterations in the

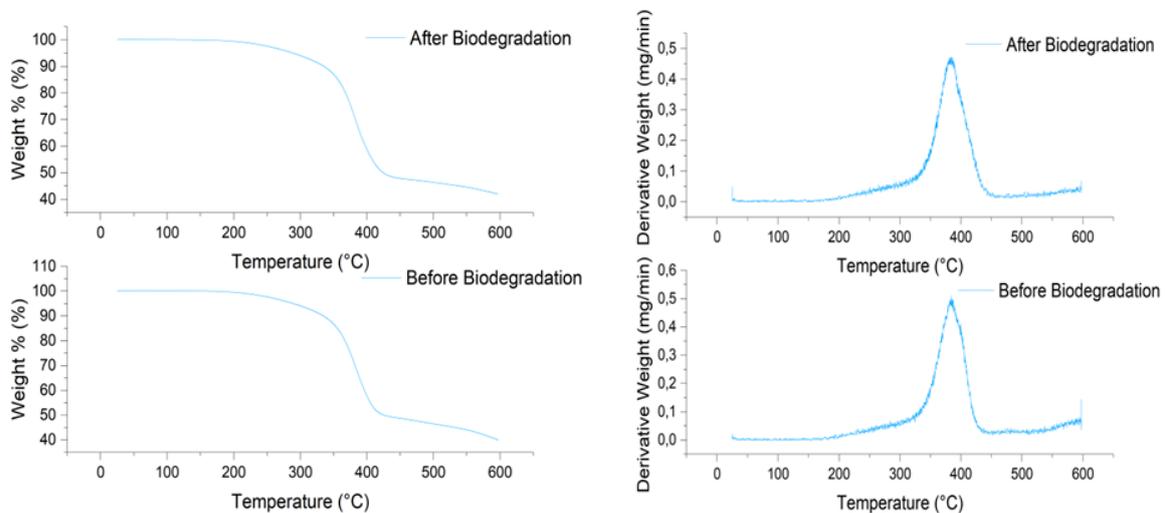
FTIR spectrum provide strong evidence of tire biodegradation by *Tenebrio molitor* larvae.

### 3) Thermogravimetry analysis

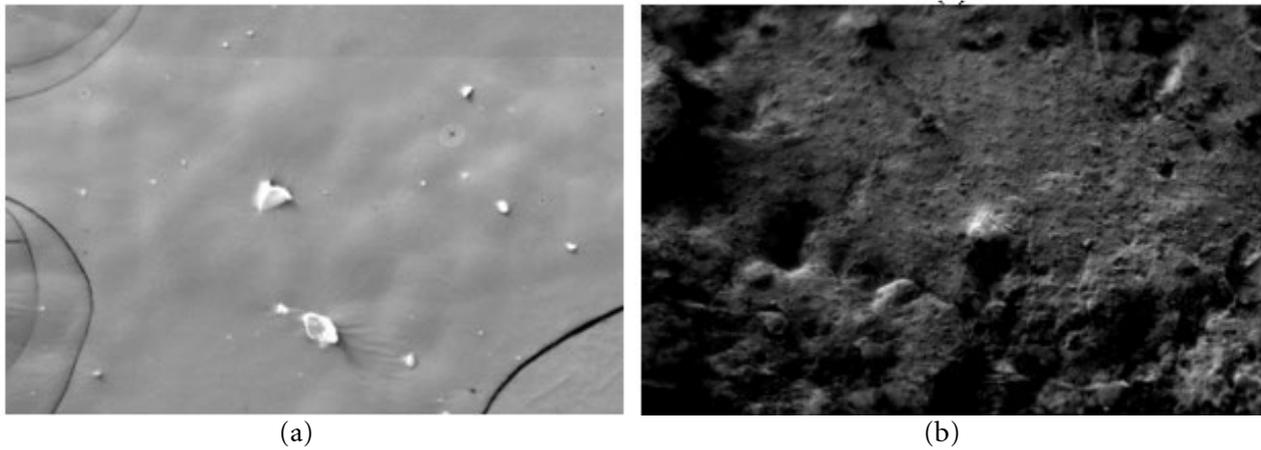
TGA was used to detect the thermal modification of the tire ingested by *T. molitor* larvae at the end of the 24-day experiment, showing patterns similar to those reported previously. Figure 4 presents the thermogravimetric (TG) curves of waste tires before and after being consumed by *Tenebrio molitor* larvae. The TG curve indicates a mass decrease, with the most significant reduction occurring at  $344.36^\circ\text{C}$  (a delta of  $6.313\text{ mg}$ ) for non-degraded tires. The peak mass decrease for tires degraded by larvae is  $6.087\text{ mg}$  at  $343.87^\circ\text{C}$ . This slight temperature difference of  $0.49^\circ\text{C}$  between the two peaks is not substantial. However, the peak shift may be attributed to the alteration in the bonding of certain compounds in the tire post-degradation. That condition is confirmed by the FTIR analysis, which reveals breaks in hydrogen and carbon chemical bonds within the polymer compounds [11, 15].

### 4) SEM Analysis

In Figure 5, the SEM analysis of tire samples reveals changes in the tire surface post-degradation by *Tenebrio molitor* larvae. Figure 5(b) displays a rougher surface with more agglomerated particles compared to the smoother surface observed in Figure 5(a) prior to degradation with the larvae. These observations suggest that the larvae's degradation process breaks bonds within the tire material, altering its texture. This physical transformation of the tire surface serves as concrete evidence of the biodegradation process facilitated by the larvae.



**Figure 4** TG/DTG curves of waste tires before and after contact with larvae.



**Figure 5** SEM images of tires: (a) before degradation at 500x magnification, (b) after degradation at 500x magnification.

### Conclusion

This study concludes that the highest tire consumption rate by *Tenebrio molitor* larvae was 0.2519 g in the 75%-OB variation, demonstrating their ability to degrade tires. However, the larvae require a nutritious diet to ensure their survival for effective degradation. The degradation process was evidenced by SEM, FTIR, and TGA analyses, which highlighted physical changes in the tires pre- and post-degradation. Future research could focus on the microflora within *Tenebrio molitor* and its potential for larger-scale tire degradation.

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