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Transforming Oil Palm Trunk (OPT) Waste into Black Soldier Fly (BSF) Larval Biomass: Investigating Pretreatment and Enrichment

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Abstract. The Indonesian government's palm oil replantation program has the potential to create an excess of oil palm trunks (OPT) in the field. Although there is an effort to obtain ethanol from the sap pressed from OPT, the OPT dregs (OPTD) remain as waste. This research investigates the potential of using OPTD as both a feed and growth medium for black soldier fly (BSF) larvae, which can be subsequently processed into animal feed. This manuscript focuses on the treatment of OPTD through maceration in water and palm oil mill effluent (POME), followed by the addition of supplementary materials, namely palm kernel meal (PKM), Azolla leaves, and solid decanter, to enhance the nutritional value and digestibility of the substrate. The effectiveness of these treatments is evaluated based on their waste-reducing capacity and the BSF larval growth. Macerating OPTD in 20% POME for 4 days was found optimal for enhancing the starch and sugar contents by 17% and 11%, respectively. The addition of PKM enhanced the growth of BSF larvae the most, resulting in a higher waste reduction index (WRI). However, it was not necessarily the most effective from the perspective of biomass conversion. The results here show that the treated OPTD mixture can serve as a viable complementary growth medium for BSF larvae.

Keywords: Black Soldier Fly (BSF), Larval Growth, Oil Palm Trunk, Waste Reduction Index

INTRODUCTION

Oil palm (*Elaeis guineensis*), a member of the Arecaceae family, is a globally cultivated crop, with Indonesia being a leading producer. In 2023 alone, Indonesia produced

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approximately 47 million tonnes of CPO, primarily from plantations on the islands of Sumatra and Borneo (BPS-Statistics Indonesia, 2024). The country has about 15.4 million hectares dedicated to oil palm cultivation.

To maintain productivity, the Indonesian government has initiated a replanting program for aging oil palm plantations. This initiative, however, results in the accumulation of old oil palm trunks (OPT), which poses a significant waste management challenge. Traditional disposal methods, such as burning or leaving it in the field, contribute to environmental harm and fail to capitalize on its potential value. Efforts to utilize OPT are underway, such as extracting sap to produce bioethanol (Norhazimah *et al.*, 2020). Still, these processes leave behind a fibrous residue known as oil palm trunk dregs (OPTD).

One potential application is to use OPTD as a growth medium for black soldier fly (BSF) larvae, which have garnered increasing attention as a sustainable solution for organic waste management and as an alternative protein source for animal feed (Lu *et al.*, 2022). Their ability to metabolically adapt and efficiently convert organic matter into high-value biomass makes them an ideal candidate for utilizing agricultural wastes, supporting their role in circular economy systems (Camperio *et al.*, 2025; Ganesan *et al.*, 2024). BSF larvae reared on various organic wastes show potential for producing high-protein biomass and lipids suitable for animal feed or biodiesel production (Lubis *et al.*, 2023). Nonetheless, standardization of feeding rates and substrate compositions remains essential to optimize large-scale applications (Diener *et al.*, 2009).

The direct use of untreated dregs for BSF larvae growth is, however, not feasible. OPT is rich in lignocellulosic biomass, containing approximately 42%–47.5% cellulose, 26%–31% hemicellulose (with xylose as the dominant sugar), and 16%–21% lignin (Mokhtar *et al.*, 2011; H'ng *et al.*, 2011). Its low protein content (<5% dry matter) limits its suitability for BSF larvae, which require higher protein levels (10%–21%) for optimal growth (Belperio *et al.*, 2024; Eggink *et al.*, 2023). Although BSF larvae can efficiently convert dietary carbohydrates into lipids via lipogenesis (Kießling *et al.*, 2023), insufficient protein results in poor larval growth and reduced biomass yield.

Studies report that rearing BSF in high-protein substrates (e.g., fish offal, fermented barley, animal waste) results in faster larval growth, higher protein retention, and better waste degradation than fiber-rich ones (Permana *et al.*, 2018; 2021a; 2021b; 2022; Andari *et al.*, 2021; Arifki *et al.*, 2024). Palma *et al.* (2019) proposed the feed C/N ratio as a representative parameter for evaluating BSF larval growth, with the optimal value of 29. Pretreatment, fermentation, and strategic blending with other biomasses are generally shown to be effective in improving feed quality and larval biomass outcomes (Ismail *et al.*, 2023; Raeiszadeh *et al.*, 2025).

Studies incorporating other oil palm by-products, such as palm kernel meal (PKM), with oil palm empty fruit bunches (OPEFB), show promising results. Diets with a 50:50 PKM:OPEFB mix significantly improved Feed Conversion Ratio (FCR), survival, and bioconversion efficiency (Bajra *et al.*, 2023; 2025). Pretreatment methods, such as chipping, shredding, fermentation, or microbial inoculation, can significantly improve the digestibility of OPT by increasing the surface area and breaking down complex lignocellulosic structures (Ismail *et al.*, 2023; Damanik *et al.*, 2023). BSF larvae are particularly adept at metabolizing simple carbohydrates such as glucose, fructose, maltose, and starch, aided by their endogenous enzymes (Wang *et al*., 2023; Guillaume *et al*., 2023). This makes pretreated or simple carbohydrate-enriched OPT especially promising when paired with appropriate protein sources. Eggink *et al*. (2023) supplemented OPT with protein-rich sources, such as food waste, soy meal, or brewery spent grains, and found an optimal protein-to-carbohydrate (P:C) ratio ranging from 1:2 to 1:4.

The findings above suggest a viable strategy of pretreating and integrating OPTD with other supplements to formulate a cost-effective and more nutritionally suitable feed for BSF larvae. This study investigates the influence of OPTD pretreatment and biomass supplementation on the BSF larval growth, and the potential of using OPTD as a feed material for BSF larvae. The pretreatment is carried out by macerating OPTD in water and palm oil mill effluent (POME), which contains diverse microbes with cellulose-degrading capabilities (Benbelgacem *et al.*, 2017), to increase the starch and sugar contents. PKM, Azolla (*Azolla microphylla*) leaves, and solid decanter (the solid by-product remaining after oil extraction from palm fruit) are used as supplementary biomasses to enhance the nutritional profile and digestibility of the substrate. These materials were also selected based on their availability in oil palm plantations and their surrounding areas. The efficacy of these treatments is assessed based on their waste-reducing capacity and the BSF larval growth.

MATERIALS AND METHODS

Raw Materials

OPTD used in this study was obtained by debarking, milling, and removing the juice from OPTs, which were collected from local oil palm plantations in Lampung, Indonesia. The size of the OPTD particles was then reduced to 18 mesh to make them more suitable as feed and growth medium for BSF larvae. POME and PKM were collected from the same plantations. Solid decanter was obtained from an oil palm plantation in Pangkalan Bun, Kalimantan, whereas Azolla was obtained locally in Bandung. A local breeder in West Bandung supplied BSF larvae (7-days old).

Pre-treatment of OPTD by Maceration

The OPTD was pre-treated by macerating in POME and water to increase its digestibility by BSF larvae. Preliminary investigations showed that the optimal results could be obtained at a diluted POME concentration of 20%. Using higher concentrations did not give significantly better results and was therefore considered inefficient. About 4 ml of POME solution was used per gram of OPTD. For comparison, similar maceration experiments in only water were also performed. The optimal maceration condition for preparing the feed (growth medium) would be determined based on the starch and sugar contents (the method will be explained later), which were measured after 1, 2, 4, and 6 days. The maceration experiments were conducted in room conditions.

Preparation of Growth Media

The macerated OPTD was mixed with Azolla leaves, PKM, and solid decanter before being given to the larvae to enrich nutrition and accelerate larval growth. PKM and solid decanter are by-products of oil palm mills, while Azolla is commonly used by local BSF breeders in their feed mixture. In this study, we use the C/N ratio as the standard for preparing the mixture, following Palma *et al*.

(2019). The amount of each additional substance was calculated from the mass balance, based on the C/N ratios of the OPTD and the substances, to yield a mixture C/N ratio of approximately 29. This approach was chosen over making the same material mass ratios over all variations, as the biomasses used here have different nutrient profiles to begin with. This would elucidate the suitability (in terms of palatability and digestibility) of the supplementary biomasses as feed material more effectively.

The C/N ratios of all the additional biomasses and OPTD were obtained from ultimate and proximate analyses based on the American Society for Testing and Materials (ASTM) standard method (explained later). The results are shown in Table 1. The total carbohydrate content in the OPTD was high, but the protein content was low, resulting in a high C/N ratio. Azolla, PKM, and solid decanter, on the other hand, had C/N ratios of 10, 21, and 9.8, respectively. Accordingly, a total of 5 combinations are determined to result in the aforementioned optimal C/N ratio: P1 = OPTD only, P2 = OPTD + Azolla [3:1], P3 = OPTD + PKM [1:2], P4 = OPTD + solid decanter [3:1], P5 = OPTD + Azolla + PKM + solid decanter [7:1:5:1].

It was important to note that these combinations on paper do not yield the protein content or the protein-to-carbohydrate ratio proposed in the other studies (Belperio *et al*., 2024; Eggink *et al*., 2023). This is understandable, as the OPTD and the three additional biomasses have lower protein contents compared to the aforementioned protein-rich substrates. Nevertheless, we want to investigate their potential as a feed and growth medium for BSF larvae, at least as a complement to more commonly used protein-rich feed materials, such as chicken feed, manure, and food waste. Chicken feed (22% protein content (Wahyudi *et al*., 2022)) was used as a control in this experiment to compare the performance of the prepared mixtures.

Table 1. Results of proximate and ultimate analyses on OPTD

Component	Value
Proximate	
Water content (%)	7.75 ± 0.03
Fat (%)	1.63 ± 0.04
Protein (%)	2.88 ± 0.01
Carbohydrate (%)	85.20 ± 0.00
Ash	2.55 ± 0.05
Ultimate	
Carbon (%)	42.62 ± 4.74
Nitrogen (%)	0.66 ± 0.08
Hydrogen (%)	6.43 ± 0.01
C/N Ratio	65.24 ± 0.30

Maggot Cultivation

In each variation, 20 g of 7-day-old larvae were fed with 40 g of growth medium (i.e., the aforementioned feed mixtures), resulting in a medium-to-larvae ratio of 2:1. The larvae were reared for 14 days until they were 21-day-old, and no additional feed was given during the rearing period. After 14 days, the larvae were manually separated from the residue using a sieve and a spatula into an empty tray. Sieving first removed the fine residue, after which the larvae were manually picked from the remaining materials using a spatula. The collected larvae were then analyzed.

The effectiveness of this cultivation process can be evaluated using some parameters related to waste reduction and larval growth (Bajra *et al*., 2025). Waste reduction index (WRI) measures the efficiency of maggots in reducing the biomass of organic waste during their feeding process (Julita *et al*., 2023). It quantifies the amount of waste converted into larval biomass or reduced through decomposition within a given period, as expressed by Eq. (1).

$$WRI = \frac{m_{\mathrm{f,0}} - m_{\mathrm{f,t}}}{m_{\mathrm{f,0}}\, t} \times 100\% \qquad (1)$$

$m_{\mathrm{f,0}}$ denotes the initial mass of the feed (growth medium), whereas $m_{\mathrm{f,t}}$ is the remaining mass after t days of feeding (Diener *et al*. 2009).

Larval growth is evaluated based on mass and length gains, which are reported as ratios to the initial values. A new parameter of fattening index (FI) is defined as the ratio of weight gain to length gain:

$$FI = \frac{(m_{\mathrm{l,t}}/m_{\mathrm{l,0}})}{(l_{\mathrm{l,t}}/l_{\mathrm{l,0}})} \times 100\% \qquad (2)$$

$m_{\mathrm{l,0}}$ and $m_{\mathrm{l,t}}$ denote the initial and final values of the larval mass, whereas $l_{\mathrm{l,0}}$ and $l_{\mathrm{l,t}}$ are those of the larval length. A lower FI thus indicates that the larvae become leaner when growing, whereas a higher FI means that they become fatter.

The rearing effectiveness of the feed mixtures is evaluated as feed conversion ratio (FCR), which is defined as the ratio of the feed given to the increase in larval mass (Broeckx *et al*., 2021):

$$FCR = \frac{m_{\mathrm{f,0}}}{m_{\mathrm{l,t}} - m_{\mathrm{l,0}}} \qquad (3)$$

A lower FCR thus means more effective biomass conversion during cultivation, and vice versa.

Analytical Methods

Proximate Analysis

Proximate analyses were conducted on both the growth media and the maggots before and after processing to determine the basic nutritional composition of the samples: moisture, fat, protein, ash, and carbohydrates.

The moisture content was determined by the gravimetric method (SNI 01-2891-1992) using an oven at 105 °C for a minimum of 3 hours. The Soxhlet method was used to measure the fat content (SNI 01-2891-1992). Hexane was used as the solvent, and the fat extraction was carried out using a Soxhlet apparatus for 6 hours.

The protein content was measured as crude protein content by using the Kjeldahl method (SNI 01-2891-1992). It consists of four main steps: digestion, distillation, NH_3 capture, and back titration. The protein content is calculated using the following formula based on the amount of nitrogen obtained.

$$\text{Protein (\%)} = \frac{(V_{\mathrm{p}} - V_{\mathrm{b}})\, N\, F}{m_{\mathrm{s}}} \times 100\% \qquad (4)$$

m_{s} is sample mass in gram. V_{p} and V_{b} are the volumes of HCl needed for NH_3 capture and back titration, respectively. N is the HCl normality (0.2 N), whereas F is the factor to convert nitrogen into protein, equal to 1.4007.

The ash content was determined by incinerating the sample in a furnace (550 °C) until only inorganic residues (minerals) remained (SNI 01-2891-1992). The weight of these residues was recorded as the ash content. Finally, the total carbohydrate content was estimated indirectly by subtracting the sum of moisture, fat, protein, and ash percentages from 100%.

Sugar and Starch Contents

The contents of simple sugars and starch were measured by using the Luff-Schoorl method, as suggested in the SNI No. 3547-2-2008 (Indonesian National Standard, 2008) and SNI No. 01-2891-1992 (Indonesian

National Standard, 1992). This method relies on the principle that the ability of reducing sugars to reduce copper (II) ions (Cu^{2+}) in an alkaline medium is reduced to copper(I) oxide (Cu_2O) (Dekker, 1950). The sample was hydrolyzed with 1 N HCl at 70–80°C for 30 minutes, followed by neutralization. It was then reacted with Luff's reagent and heated in a boiling water bath for 10 minutes. The remaining unreduced copper was titrated with 0.1 N sodium thiosulfate using starch as an indicator to determine the reducing sugar and total sugar contents.

Statistical Analysis

All experiments were performed in duplicate, while analyses were conducted in triplicate. Microsoft Excel 2021 and Minitab 21.4.1 were used to analyze the data. One-way ANOVA with 95% confidence level and Duncan test were performed to statistically evaluate the influence of feed mixtures on BSF larval growth.

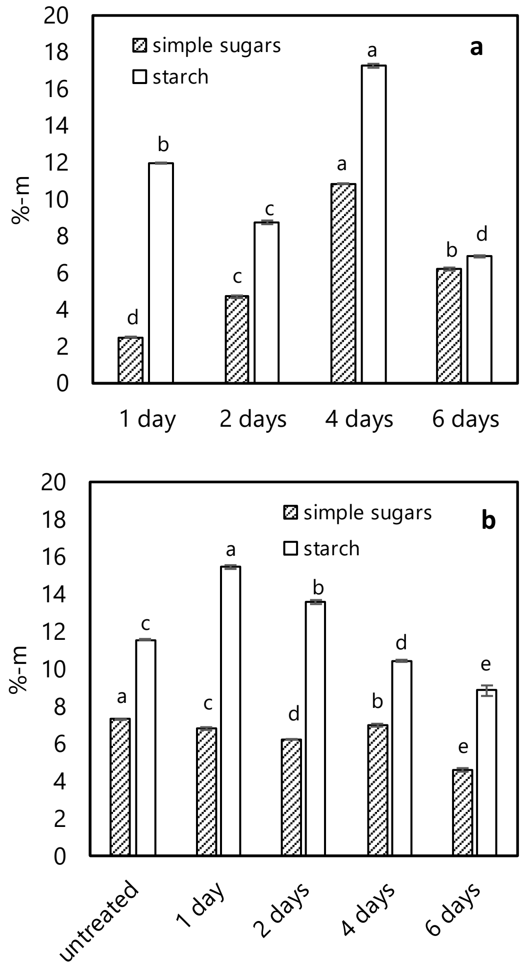

Fig. 1: Sugar and starch contents in OPTD obtained after different days of maceration using (a) diluted POME and (b) only water.

RESULTS AND DISCUSSION

Treatments of OPTD

Preliminary trials were conducted by feeding BSF larvae with unprocessed palm sap dregs. Observations after several days showed that BSF larvae could not grow when fed with only untreated OPTD. The first treatment involved size reduction to make the OPTD finer, allowing it to be easily consumed by the BSF larvae. The pulverized OPTD was soaked for 4 days before being given to BSF larvae. The preliminary experiment showed that the larvae tend to consume finer OPTD. Additionally, the particles had to be smaller than 18 mesh for the larvae to consume. This size was thus used as a standard for the next experiments.

The results of OPTD maceration in water and POME are shown in Figure 1. ANOVA gave p-values less than 0.001 for every observed variable, indicating significant differences among variations. The highest starch and sugar contents were found after 4 days of maceration in 20% POME solution, as shown in Figure 1a. The role of maceration in increasing the starch content is apparent in the starch contents of OPTD and POME solutions. During the maceration days, the sugar and starch contents were found to fluctuate. Between the 1st and 2nd day, a breakdown of starch into glucose could have occurred, as indicated by the temporary decrease in starch content. Here, the activity of microorganisms in POME, hydrolysis, and environmental conditions could play a role (Teoh and Don, 2011; Soleimaninanadegani and Manshad, 2014).

Maceration in only water, on the other hand, resulted in a rapid increase in starch content. It, however, decreased over time. This result can be attributed to the hydrolysis of the starch, which occurs when starches are exposed to acids, enzymes, or simply soaked in water (Nasution *et al.*, 2023; Olawoye *et al.*, 2023). Interestingly, water maceration resulted in relatively stable sugar content, except after 6 days. Based on these results, maceration in a 20% POME solution for 4 days was chosen as the treatment condition for OPTD before utilization, as it yielded the highest starch (17.27%) and sugar (10.86%) contents.

Cultivation of BSF Larvae

Figures 2 and 3 show the results of BSF larvae cultivation using the prepared mixtures. ANOVA was performed on the data obtained from the feed mixtures, yielding p-values of less than 0.05, with the highest p-value obtained for WRI (p-value = 0.039). If the control data were included, all p-values become lower than 0.001, indicating even more significant differences, as apparent in the figures.

From Figure 2, it can be seen that the P3 mixture resulted in high WRI and an increase in larvae mass, mainly due to the presence of PKM, which is more nutritious than OPTD to begin with. The higher preference of BSF larvae to consume PKM was also confirmed in our other experiments (not shown here). The other materials (i.e., Azolla and solid decanter), had limited effects on stimulating larval growth, on the other hand. Furthermore, they showed a negative effect on the waste-reducing capacity, as indicated by the lower WRI compared to that of P1.

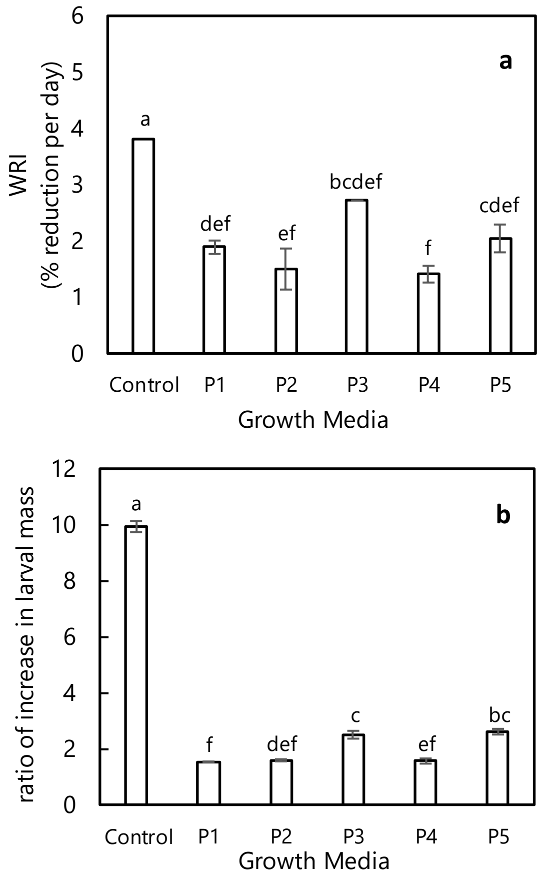

Fig. 2: (a) The average daily waste reduction index (WRI) and (b) the increase in dry mass of BSF larvae fed with various mixtures of substances and OPTD macerated in the 20% POME solution for 4 days.

It is important to note that the remaining mass used to calculate the WRI consists of a mixture of OPTD, the added materials, and the excretion products of the larvae. Separation of these components was not possible. Additionally, the OPTD was given in an excessive amount, as it serves not only as feed but also as a cultivation medium. These hinted at two possibilities. First, the consumption of Azolla and the solid decanter was rather limited. With these materials present, the amount of OPTD decreased initially, resulting in less WRI. Another possibility is that the BSF larvae did not digest the Azolla and the solid decanted, although the materials could have been consumed. Confirmation was unfortunately not yet possible due to the difficulties in conducting remnant separation and metabolic analysis on the larvae.

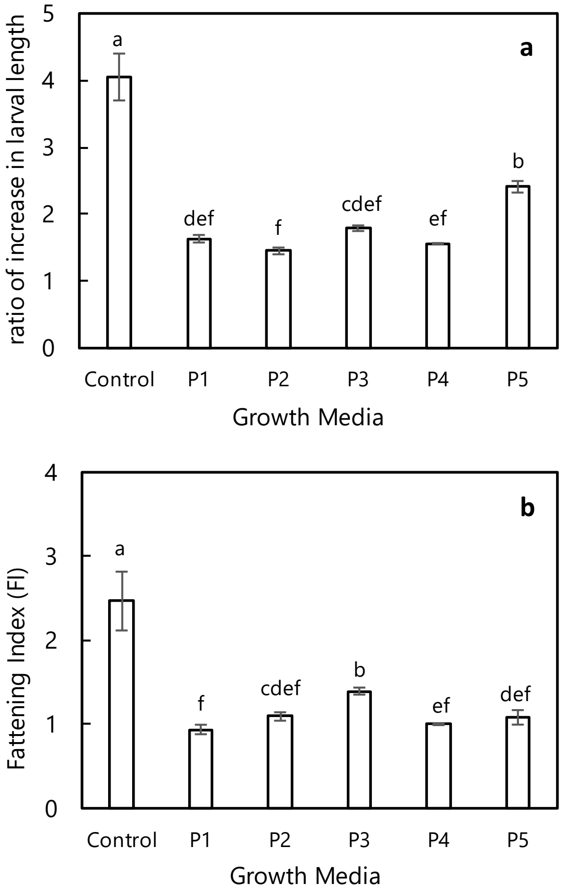

Fig. 3: (a) The increase in larval length and (b) the Fattening Index (FI) of BSF larvae fed with various mixtures of substances and OPTD macerated in the 20% POME solution for 4 days.

The increase in larval length in Figure 3a shows a different trend compared to larval mass in Figure 2b. While the addition of PKM still resulted in better larval growth compared to when only Azolla or solid decanter was added, it was outperformed by the addition of all three materials combined. From the FI shown in Figure 3b, the additional biomasses made the larvae fatter to some degree and PKM had the biggest contribution. While protein is necessary for larval growth, fattening could be more influenced by fat. PKM has a higher fat content (3.11%) compared to Azolla (0.06%) and solid decanter (0.25%). Additionally, among those three PKM, it also has the highest carbohydrate content (5-7 times). BSF larvae could transform carbohydrate into lipid through lipogenesis in a situation where their food is low in protein but high in carbohydrate (Kieβling *et al.*, 2023), i.e., the condition found here.

The variations P1-P5 yielded the FCR values of 3.75, 3.41, 1.34, 3.66, and 0.99, respectively. Variation P5 thus yielded the most effective biomass conversion (i.e., the lowest FCR), although the WRI (2.04%/day) remains lower than that of P3 (2.72%/day). For comparison, rearing BSF on fruit and vegetable substrates, respectively, resulted in WRI of 3.57% and 3.35% per day (Rampure and Velayudhannair, 2023). However, the FCR values are very high: 30.49 and 32.15, respectively, indicating very inefficient biomass conversion. A study conducted by Bajra *et al.* (2023) on oil palm EFB supplemented with PKM yielded an optimal FCR of 3.98 and a WRI of 5.39% per day. The data indicate that the current study exhibits relatively better rearing efficiency, as evidenced by the lower FCR values, although its waste-reducing capacity is comparatively lower.

In general, all the combinations tried here could not yield the performance levels close to that of the control, which suggests that they would be more of a partial rather than a full substitute to the more commonly used feed materials, like demonstrated in the previous studies (Bajra *et al.*, 2023; 2025; Eggink *et al.*, 2023). Combining different materials could result in not only additive, but also synergistic effects. For example, mixing dairy manure (lignocellulose-rich) with chicken manure, which helps diversify the microbial community, has been shown to improve cellulose degradation by BSF larvae (Zhang *et al*., 2023).

CONCLUSIONS

This study demonstrated the potential and limitations of using OPTD as a growth medium for BSF larvae. The treatments were carried out to optimize the digestibility and nutrient profile of OPTD, as well as to enhance the BSF larval cultivation. It was found that the OPTD must be smaller than 18 mesh for the larvae to consume. Maceration with POME could result in higher sugar and starch contents in OPTD, although a longer time is needed. The optimal maceration was achieved using a 20% POME solution for 4 days. The sugar and starch contents increased rapidly with water maceration but subsequently decreased rapidly. Addition of PKM to the OPTD mixture boosted the growth of BSF larvae, as evidenced by higher WRI and mass gain. In contrast, Azolla and solid decanter had limited effects on larval growth and negative impacts on WRI. Fattening of BSF larvae is contributed more by the addition of PKM, which could promote the availability of fat.

The results presented here indicate that while OPTD is potentially a growth medium and feed for BSF larvae, it can only partially replace the more commonly used feed. Investigations into the application of the optimal OPTD-based feed, along with more common substrates on a larger scale, could be a continuation of the current research. It must be acknowledged that here the nutritional quality of the feeds is primarily based on the C/N ratio. The other nutritional contents (starch and sugars) were analyzed only for optimizing the OPTD pretreatment. This study is also limited by the difficulty in identifying and separating the remaining biomasses, and thus, the feeding preference of BSF larvae could not be investigated.

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