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UTILIZATION OF PALM KERNEL BY-PRODUCT IN BIOCONVERSION OF BLACK SOLDIER FLY LARVAE: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Palm kernel by-product (PKB) refers to the waste material, mainly solid and fibrous, that remains after the oil has been extracted from the palm fruit kernels. The utilization of PKB in various applications, including bioconversion using Black Soldier Fly (BSF) larvae has promoted sustainable waste management and resource recovery. Many researchers have begun investigating PKB potential in bioconversion, exploring methods to modify its nutritional composition and assess the bioconversion results. Therefore, this systematic literature review seeks to comprehensively evaluate the potential of PKB in BSF larvae bioconversion, emphasizing its influence on BSF larvae growth performance and providing an in-depth characterization of the biomass. The Reporting Standard for Systematic Evidence Syntheses (ROSES) framework was employed in this study. The search strategy was developed by identifying key terms derived from the research question and objective resulting in 11 articles published between 2004 and 2024 being systematically reviewed. The findings specify that PKB can be utilized in unmodified and modified forms, with modifications through mixing with other substrates as well as fermentation. Although PKB can be utilized as a substrate for BSF larvae in its unmodified form, researchers have found that modifying the substrate can significantly enhance its nutritional value as well as improve the growth performance of BSF larvae and its biomass. This review indicates that the modified form of PKB holds substantial potential as a feed source for BSF larvae, facilitating the transformation of PKB into nutrient-rich larvae biomass that is high in protein or lipids.

Keywords: Black soldier fly larvae; palm kernel by-product; bioconversion, biomass

ABSTRAK

Produk sampingan isirung sawit (PKB) merujuk kepada bahan buangan, terutamanya pepejal dan serat, yang tinggal selepas minyak diekstrak daripada isirung buah sawit. Penggunaan PKB dalam pelbagai aplikasi, termasuk biopenukaran menggunakan larva Lalat Askar Hitam (BSF), telah menggalakkan pengurusan sisa yang mampan dan pemulihan sumber. Ramai penyelidik telah mula mengkaji potensi PKB dalam biopenukaran, meneroka kaedah untuk mengubah komposisi nutrisinya dan menilai hasil biopenukaran. Oleh itu, ulasan literatur sistematik ini bertujuan untuk menilai secara komprehensif potensi PKB dalam biopenukaran larva BSF, dengan penekanan diberikan terhadap kesannya kepada prestasi pertumbuhan larva BSF serta memberikan pencirian terperinci terhadap biojisim yang dihasilkan. Rangka kerja Piawaian Pelaporan untuk Sintesis Bukti Sistematik (ROSES) telah digunakan dalam kajian ini. Strategi pencarian dibangunkan dengan mengenal pasti istilah utama yang diperoleh daripada soalan dan objektif kajian, menghasilkan 11 artikel yang diterbitkan antara 2004 dan 2024 untuk disemak secara sistematik. Hasil kajian menunjukkan bahawa PKB boleh digunakan dalam bentuk yang tidak diubah suai atau yang telah diubah suai, dengan pengubahsuaian dilakukan melalui pencampuran dengan substrat lain serta fermentasi. Walaupun PKB boleh digunakan sebagai substrat untuk larva BSF dalam bentuk asalnya, penyelidik mendapati bahawa pengubahsuaian substrat dapat meningkatkan nilai nutrisinya dengan ketara serta memperbaiki prestasi pertumbuhan larva BSF dan biojisim yang dihasilkan. Ulasan ini menunjukkan bahawa bentuk PKB yang diubah suai mempunyai potensi besar sebagai sumber makanan untuk larva BSF, memudahkan transformasi PKB menjadi biojisim larva yang kaya dengan nutrien, sama ada tinggi protein atau lipid.

Kata kunci: Larva lalat askar hitam; produk sampingan isirung sawit; biopenukaran; biojisim

INTRODUCTION

Oil palm also known as African oil palm, has the scientific name *Elaeis guineensis* Jacq. This name is derived from the Greek word *elaion*, meaning oil and *guineesis*, suggesting its origin from Equatorial Guinea (Embrandiri et al. 2015). This palm species, which belongs to the family Arecaceae, can be grown in the tropics of Asia, Africa, and Central and South America, with Malaysia being one of the leading countries cultivating this oil-containing plant as a main agricultural crop. The development of the oil palm plantation in Malaysia began in 1911, with the first estate established at Rantau Panjang, Selangor, by the Frenchman Henri Fauconnier (Ahmad et al. 2014). Since the industry continuing develop, Malaysia has consistently maintained the oil palm planting area with 5.74 million hectares recorded in 2021, 5.67 million hectares in 2022, and 5.65 million hectares in 2023 (MPOB 2021, 2022, 2023).

Oil palm cultivation is primarily focused on its oils, with the oil palm fruits producing two types of oil known as crude palm oil (CPO) and crude palm kernel oil (CPKO) (Ahmad et al. 2014). These oil palm products are processed respectively at the oil palm mill and the kernel crushing plant undergoing a series of stages including extraction that result in a significant amount of liquid and solid waste (Parveez et al. 2021). In countries with significant palm oil production, effective and sustainable waste management is crucial, as the waste is generated throughout the year. With the increase in global demand, palm oil and its associated wastes are produced in increasing quantities. Specifically, to the production of CPKO from the kernels of the palm fruits, the process generated palm kernel by-product (PKB) (Hem et al. 2008). Referring to the data, the production of CPKO reached approximately 2.05 million tonnes in 2021, increased to 2.10 million tonnes in 2022, and further rose to 2.12 million tonnes in 2023. Concurrently, PKB production was approximately 2.30 million tonnes in 2021, 2.36 million tonnes in 2022, and 2.33 million tonnes in 2023, reflecting a consistently high production rate of CPKO as well as PKB (MPOB 2021, 2022, 2023). Given this, effective management of PKB is essential to address its significant accumulation and mitigate unwanted environmental impacts.

PKB is referring to waste generated from the palm kernel processing. The process involved extracting oil from the palm kernel resulting in palm kernel oil and by-product known as palm kernel cake (PKC), palm kernel meal (PKM) and palm kernel expeller (PKE), depending on the methods of extraction used. In Malaysia, three methods of palm kernel oil extraction have been reported such as mechanical extraction, solvent extraction, and pre-pressing followed by solvent extraction. The PKB from the mechanical extraction method is referred to as PKC or PKE, whilst that from the solvent extraction method is called PKM (Saw et al. 2012). For clarity in this review, the terms PKC, PKM, and PKE are used interchangeably according to each article referenced.

According to Abdullah and Sulaiman (2013), basic principles of waste management encompass key strategies such as minimization, recycling, recovery of energy, and responsible disposal which are designed to enhance the sustainability of waste management systems. Despite these principles, conventional waste management practices often fail to fully implement them. This is particularly evident in the waste management of palm waste, such as PKB, which has traditionally been accumulated through open dumping and not optimally utilized. This approach results in environmental problems, where the accumulation of PKB in open areas leads to increased greenhouse gas emissions, contributing to elevated air pollution and exacerbating global warming (Embrandiri et al. 2015; Visvini et al. 2022). Although PKB is a waste, it holds considerable nutritional value, with a composition of approximately 18-20% crude protein, 12-20% crude fat, and 13-20% crude fibre (Sundalian et al. 2021). This nutritional profile highlights the potential of PKB as a valuable resource, offering opportunities for optimization and enhanced utilization. Furthermore, due to its availability and continuity of production, oil palm waste serves as a reliable resource for renewable solutions. Given the availability of alternative conversion technologies, optimizing PKB utilization through bioconversion is both feasible and recommended (Abdullah & Sulaiman 2013).

In context utilization of PKB as animal feed, inclusion levels in feed vary among livestock species. Ruminants are better suited to the nutritional profile of PKB, while non-ruminants face limitations due to their high crude fibre content. According to Mohamed and Alimon (2003), higher inclusion levels are recommended for ruminants, such as beef cattle (50-80%) and dairy cattle (30-50%), while lower levels are suggested for non-ruminants, including swine (15-25%), poultry (15-25% for layers and 15-20% for broilers), and freshwater fish (10-20%). These variations reflect the differing digestibility and nutritional needs of each species, highlighting the necessity for modification in the feed formulations.

Given the limitations in utilizing PKB as animal feed, researchers have been exploring methods to enhance digestibility while implementing effective sustainable PKB waste management. In this regard, insect-based bioconversion, a process that utilizes insect species to biologically convert organic waste into high-value biomass through metabolic process has emerged as a promising approach (Purnamasari & Khasanah 2022). This innovative method stands out for its economic feasibility, environmental sustainability, and technical viability. Insect-based bioconversion not only addresses waste management challenges but also generates nutrient-rich animal feed from biomass produced, significantly maximizing PKB utilization (Siddiqui et al. 2024).

Insect-based bioconversion requires effective bioconversion agents, and the black soldier fly, BSF (*Hermetia illucens*) stands out as excellent in many aspects (Gunggot & Lardizabal 2024). One of the aspects is its larvae adaptability to feed various organic wastes (Surendra et al. 2020; Tambeayuk et al. 2023). Previous studies have shown that Black Soldier Fly (BSF) larvae can feed on kitchen wastes (Li et al. 2022), various fruit wastes such as banana peels and coconut testa (Putra et al. 2020), animal manure such as cow dung (Shumo et al. 2019) and sheep manure (Julita et al. 2018) as well as agricultural waste including oil palm waste (Visvini et al. 2022). Besides that, incorporating the BSF larvae into animal feed offers additional advantages. Due to their ability to consume and convert a wide range of organic waste into valuable biomass such as protein, BSF larvae can serve as an alternative protein source in animal feed, thereby reducing feed costs and reliance on imported feed commodities (van Huis 2013). In addition, cultivating BSF larvae for bioconversion systems is considered easy, cost-effective, and efficient due to the insect's short life cycle. Typically, BSF completes its full development within 39 to 47 days, encompassing the egg stage (approximately 4 days), larval stage (13 to 18 days), prepupal stage (around 7 days), pupal stage (about 10 days), and adult stage (5 to 8 days) (Surendra et al. 2020). Furthermore, from a safety perspective, this species poses no threat to humans, as adult flies do not bite or feed (Purnamasari & Khasanah 2022).

Apart from that, the aspect of organic substrate use is also crucial in the BSF larvae bioconversion process. The substrate serves as both a growth medium and feed source for BSF larvae (Fitriana et al. 2021; Nayak et al. 2024). The choice and preparation of organic substrates in BSF larvae bioconversion are critical for optimizing the efficiency and outcomes of the bioconversion process. Previous studies have found that, the growth performance of BSF larvae is greatly influenced by the feed source provided mainly due to the nutritional values of the substrate. This situation can be caused by an imbalanced diet and limited digestibility mainly due to the use of a single substrate or substrates that contain high crude fibres. Eventually, this situation can be improved by mixing or blending different waste types with optimum inclusion ratio, thus providing balanced nutrients needed for BSF larvae to grow (Julita et al. 2018; Li et al. 2022). Additionally, substrates with high-crude fibre can be treated through a fermentation process with specialized microorganisms adapted to the fermentation process, hence helping degrade the fibres and make the substrate more favourable for BSF larvae (Gao et al. 2019).

Expanding the use of PKB as a substrate for BSF larave bioconversion, offers a significant advancement in addressing sustainability management issues within the oil palm industry. This strategy not only tackles the waste management issue but also creates a new opportunity for valuable biomass resources. As noted by Mohamed and Alimon (2003) and Widjaja and Utomo (2021), solid palm oil waste is a promising livestock feed ingredient and an excellent medium for cultivating BSF larvae, which in turn can provide a valuable source of protein, fat, and energy. Realizing the potential, recent studies have explored using PKB as a feed substrate for BSF larave with ongoing investigating application of PKB-reared BSF larvae. Therefore, this study aims to systematically review PKB as a substrate to feed BSF larvae and examine the effects of PKB-based substrates on BSF larave growth performance and the nutritional value of biomass produced.

MATERIALS AND METHODS

Review Protocol - ROSES

This study followed the Reporting Standard for Systematic Evidence Syntheses (ROSES) as its review protocol. Developed specifically for environmental management and conservation research, ROSES offers a comprehensive and structured framework for conducting systematic literature reviews (SLR) in these disciplines (Haddaway et al. 2018). In contrast, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), although widely used, was originally designed for reviews in the healthcare sector and is less suited to the methodological diversity found in environmental research. Besides, PRISMA's framework does not adequately accommodate narrative, qualitative, or mixed method approaches that are often essential in conservation and environmental management reviews.

Following ROSES principles, the objectives of this study were explicitly defined to address the research question effectively. As noted by Pullin and Stewart (2006), SLR begins with a clearly defined research question, which is critical for generating key elements to shape the search strategy. In this study, the main research question is: What are the effects of PKB-based substrates treatments on the growth performance and nutritional composition of BSF larave biomass?

Through utilizing the ROSES guidelines, the review process has three main steps: (1) systematic searching strategy, (2) quality assessment, and (3) data extraction and analysis. The systematic search strategy involved three specific processes: identifying relevant articles, screening these articles for relevance and assessing eligibility for inclusion (Shaffril et al. 2020). Literature searches were conducted from August 19 to August 23, 2024, utilizing scientific online databases such as Web of Science (WoS), Scopus, Google Scholar, and PubMed to source primary data. Following the literature search, a quality assessment was performed to ensure that all retrieved articles aligned with the objectives of this review. Once the selected articles were finalized, the data extraction and analysis phase commenced. All relevant data from the selected articles were extracted in accordance with the study's objectives and research question. The procedural steps undertaken in this study are illustrated in Figure 1.

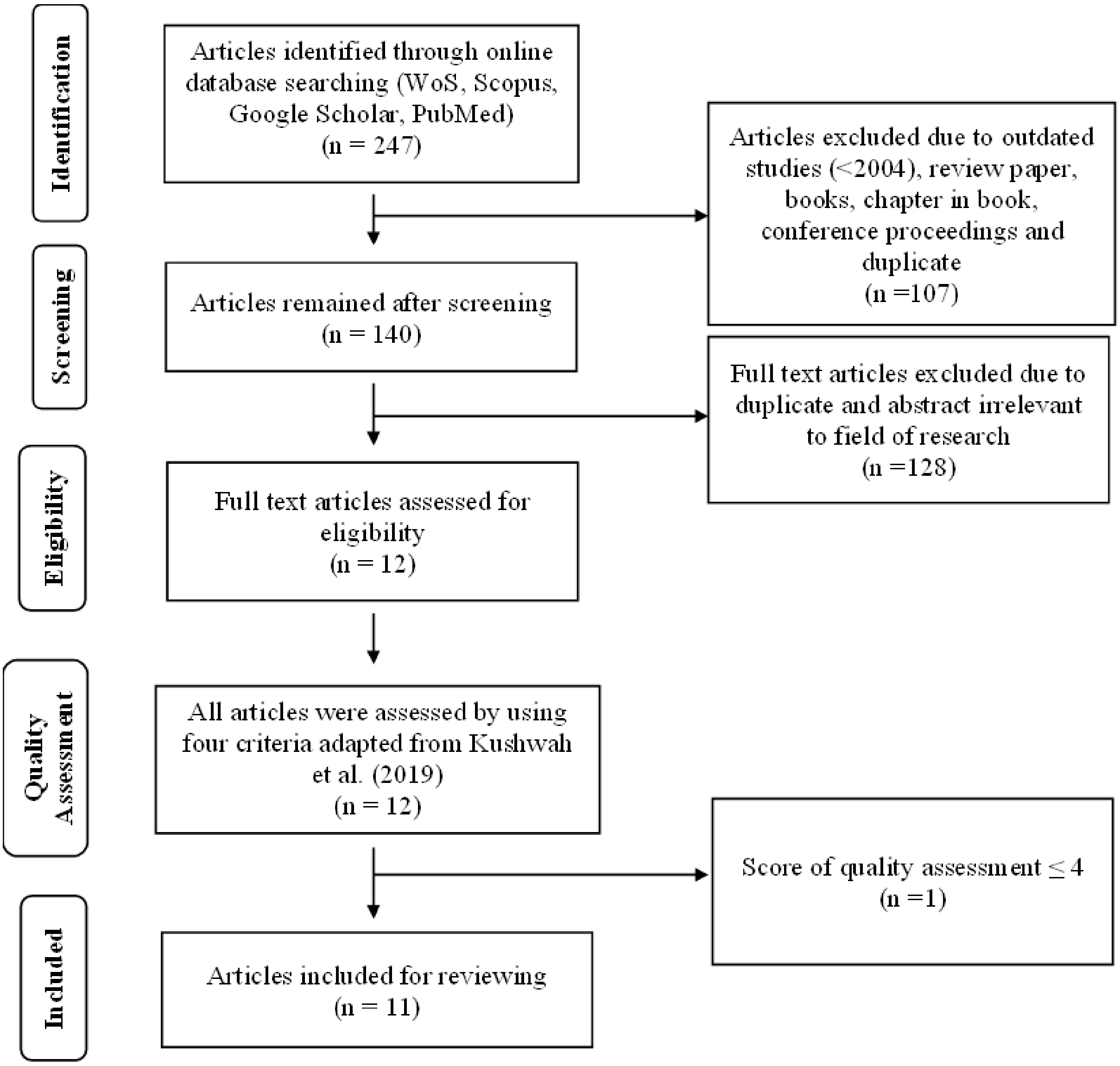

Figure 1. Research flow diagram

Systematic Searching Strategy
Identification
The identification of key terms was the initial step in the systematic searching strategy employed in this study. The primary keywords developed for this research included "black soldier fly (BSF)," "palm kernel by-product," "performance," and "biomass." These keywords were formulated by referencing the research questions and objectives of this review, as well as keywords from previous studies. To ensure a comprehensive search strategy across the selected databases, the main keywords were enriched by exploring synonyms and variations of the terms. This enrichment process facilitated a more comprehensive search and increased the likelihood of retrieving relevant literature. Both the primary and enriched keywords are summarized in Table 1. After identifying these keywords, a complete search string was constructed. This search string was developed using phrase searching, field code functions (such as title, abstract and keywords), and Boolean operators. The full search string encompassed keywords organized into four distinct categories, with terms within each category connected by the operator "OR" and the categories themselves combined using "AND". The first category searched for articles related to insect-based bioconversion specifically on BSF.

The second category searched for articles reporting on palm kernel by-product as rearing substrate. The third category concentrated on articles that evaluated BSF larvae performance, while the fourth category targeted articles concerning nutritional biomass production. The complete search string used in the selected databases is presented in Table 2.

Table 1. The main and enriched keywords

Main Keywords	Enriched Keywords
BSF	Black Soldier Fly, *Hermetia illucens*
Palm kernel by-product	Palm kernel cake, palm kernel meal, palm kernel expeller
Performance	Growth, Development
Biomass	Protein, lipid

Table 2. The search string

Database	Search String
WoS	(“Black Soldier Fly” OR “*Hermetia illucens*”) AND (“Palm Kernel Cake” OR “Palm Kernel Meal” OR “Palm Kernel Expeller”) AND (“Growth” OR “Development”) AND (“Protein” OR “Lipid”)
Scopus	TITLE-ABS-KEY ((“Black Soldier Fly” OR “*Hermetia illucens*”) AND (“Palm Kernel Cake” OR “Palm Kernel Meal” OR “Palm Kernel Expeller”) AND (“Growth” OR “Development”) AND (“Protein” OR “Lipid”))
Google Scholar	(“Black Soldier Fly” OR “*Hermetia illucens*”) AND (“Palm Kernel Cake” OR “Palm Kernel Meal” OR “Palm Kernel Expeller”) AND (“Growth” OR “Development”) AND (“Protein” OR “Lipid”)
PubMed	(“Black Soldier Fly” OR “*Hermetia illucens*”) AND (“Palm Kernel Cake” OR “Palm Kernel Meal” OR “Palm Kernel Expeller”) AND (“Growth” OR “Development”) AND (“Protein” OR “Lipid”)

Screening

Identified research articles were required to meet the inclusion criteria related to publication timeline, document type and language for inclusion in this review. This second step of the systematic searching strategy was facilitated through an automatic sorting function available in each database. Additionally, any duplicate research articles identified during this process were excluded. The criteria for inclusion and exclusion were summarized in Table 3.

Table 3. The inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Publication timeline	2004-2024	<2004
Document type	Research articles	Review, book chapter in a book, conference proceeding
Language	English	Non-English

Eligibility

The third step of the systematic searching strategy involved a manual screening of the identified research articles by the authors which included a thorough review of the title, abstract and main contents. This meticulous process was essential to ensure that each article was relevant to the topic, aligned with the review's objectives and addressed the research question. Any articles deemed irrelevant to the field of research were systematically excluded from the review.

Quality Assessment

The second step based on ROSES guidelines which focused on quality assessment was conducted by the authors in this study by scoring each identified research article according to four criteria adapted from (Kushwah et al. 2019). The criteria utilized for this quality assessment were summarized in Table 4. Each criterion's score was calculated and summed to obtain a final score. Only articles that received a score exceeding fifty per cent of the maximum possible score of 8 were included in this review (Behera et al. 2019).

Table 4. Quality assessment

Quality Assessment	Description
QA 1	The study contains a collection of data evidence with analysis. The possible answers are quantitative, qualitative, and no evidence with scores of +2, +1.5 and 0, respectively.
QA 2	The study elaborates advantages and limitations aspects of the study. The possible answers are yes, partially and no with scores of +2, +1 and 0, respectively. The partial is considered only when one of the other two has been elaborated.
QA 3	The output of the study is justifiable. The possible answers are yes, partially and no with scores of +2, +1 and 0, respectively. The partial score is given when the technique is explained in a limited context.
QA 4	The study was published in a reliable and recognized source. The possible answer and score are +2 if the summation of citation and H index exceeds 100, +1.5 if the summation is between 99 and 50, +1 if the summation is between 49 and 1 and lastly, 0 if the summation of citation and H index is 0.

Data Extraction and Analysis

Upon identifying the eligible and selected research articles for this review, the required data from these 11 articles were meticulously extracted in alignment with the objectives and research questions of this review. This third step, in accordance with ROSES guidelines, involved a comprehensive review of the abstract, results and discussion sections of each article. The extracted data encompassed references, substrate modification and key results of BSF larvae development and productivity as detailed in Table 5. Data extraction was carried out by NS and subsequently verified by Ishak AR and Dom NC to ensure accuracy and consistency.

Table 5. A compilation of research articles that investigated the use of palm kernel by-products as a feed component for BSF larvae and the associated effects

No.	Reference	Substrate Modification	Black Soldier Fly (BSF) Larvae Development and Productivity	
			Growth Performance	**Biomass Profiling**
1.	Binsin et al. (2023)	No substrate modification. Only four different individual substrates, namely food waste (FW), coconut endosperm (CE), palm kernel expeller (PKE) and chicken manure (CM).	-100% larval survivability from CM, FW and CE treatments. PKE produced the lowest larval survivability of 94%. -Larval development time of (18.74±0.55 days), (16.87±0.05 days) and (16.33±0.04 days) from CW, PKE and FW respectively.	-
2.	Rasdi et al. (2023)	First stage of the experiment used unmodified PKE, soybean waste (SW), coconut milk waste (CMW). Second stage of the experiment involved substrate modification through mixing SW and PKE at various ratios; 20:80, 30:70, 50:50, 70:30, 80:20 (w/w).	-Highest mean length of 22.67mm and mean weight of 0.27g from unmodified PKE. Lowest mean length of 18.33mm and mean weight of 0.15g from unmodified CMW. -The mixture at a ratio 80:20 of SW to PKE, the highest BSF larvae length of 22.67mm and weight of 0.28g and the 20:80 ratio recorded the lowest BSF larvae length of 19.67mm and weight of 0.17g	-
3.	Bajra et al. (2023)	Substrate modification through percentage mixing of palm kernel meal (PKM) with coarse and fine oil palm empty fruit bunch (OPEFB) in a specified ratio: 100:0:0, 80:0:20, 80:20:0, 50:0:50, 50:50:0, 20:0:80, 0:0:100, 0: 100:0.	-Final BSF larvae weights ranging from 100 mg to 150 mg and below 50 mg. -The highest survival rate of 96.67% from the BSF larvae fed on mixing of 80% PKM and 20% fine OPEFB.	-

4.	Raksasat et al. (2021)	Substrate modification through mixing of sewage sludge to PKE at various ratios namely 5:0, 4:1, 3:2, 2:3, 1:4, 0:5.	-Lowest larvae weight: 14.38mg/larvae. -Highest larvae weight: 46.99mg/larvae. -At a 5:0 ratio, rearing duration 27 days while at 1:4 and 0:5 ratio where the proportion PKE the high only took 13 days.	-Highest lipid yield of 17% at a mixing ratio 3:2. -Lauric acid percentage at various ratio: 5:0 (19.56%), 4:1 (24.28%), 3:2 (53.36%), 2:3 (21.37%), 1:4 (7.91%) and 0:5 (16.92%). -Oleic acid percentage at various ratio: 5:0 (24.37%), 4:1 (20.29%), 3:2 (9.22%), 2:3 (5.0%), 1:4 (18.56%) and 0:5 (11.91%).
5.	Nugroho et al. (2023)	Seven treatments consisted of only PKM, only fish feed pellet (FFP), combination of PKM: FFP (1:1) and combination PKM: FFP (1:1) with various concentrations of fructose; 2.5, 5, 7.5, 10 (%).	-The highest BSF larvae weight: 0.24±0.004g. -Survival rate: 94.00±2.94% (PKM), 95.25±0.47% (FFP), 93.00±0.70% (PKM: FFP), 95.00±1.25% (PKM: FFP 2.5% fructose), 96.50±1.25% (PKM: FFP 5% fructose), 97.00±2.38% (PKM: FFP 7.5% fructose) and 96.50±1.25% (PKM: FFP 10% fructose).	-High crude protein: 55.68±2.30%. -Additional of fructose decreased crude fat in ranged (4.45±0.09% to 4.77±0.24%). -High relative concentration of fatty acid: lauric acid in range 11.22±0.02% to 19.75±0.82%.
6.	Nugroho et al. (2022)	Fermented PKM and cow manure (CM) with EM4 and sugar.	-The length of BSF larvae: reached 20 mm (fermented CM), 18 to 18.5 mm (fermented PKM) -The weight of BSF larvae: 0.195 to 0.2g (fermented CM) group ranged from 0.195 to 0.2 g, 0.18 to 0.185 g. (fermented PKM).	-Crude protein: 47.34±0.04% (fermented PKM) and 46.64±0.04% (fermented CM). -4.31±0.02% crude lipid of fermented PKM and 4.47±0.02% (fermented CM). -Dominant BSF larvae-fed fermented PKM fatty acid contents: 29.27±0.19 (lauric acid) and 22.10±0.10% (heptadecanoic acid). -Dominant BSF larvae-fed fermented CM fatty acid contents: 7.15±0.03% (myristoleic acid), 17.59±0.10% (palmitoleic acid), 4.52±0.16% (linolenic acid), 10.18±0.09% (arachidic acid)

7.	Damanik et al. (2023)	Fermented PKM with EM4 and molasses at different durations: 2, 3 and 4 days and PKM soaked in water for 4 days.	-BSF larvae survival rate at different fermented PKM duration: 2-days (99.88±0.44%), 3-days (99.87±0.48%), 4-days (99.72±1.09%), 4-days water soaked PKM (99.80±0.76%) and chicken feed (100.00±0.00%). -BSF larvae development time at different fermented PKM duration: 2-days (17.00±0.00 days), 3-days (17.60±1.34 days), 4-days (20.60±1.34 days), 4-days water soaked PKM (23.60±1.34 days) and chicken feed (15.80±1.64 days). -BSF larvae growth rate across fermented PKM not significantly different.	-
8.	Nugroho et al. (2024)	Fermented PKM with EM4 and molasses with the addition of various sugars; fructose, glucose, maltose, sucrose.	-The addition of various sugars in the fermented PKM had no significant effect on the final weight of the BSF larvae. -The addition of glucose, the highest BSF larvae length (1.64cm).	-The highest crude protein (52.26±0.29%) with BSF larvae reared on fermented PKM with addition of fructose. -Highest lauric acid (22.60±0.34%) from BSF larave reared on fermented PKM with addition of glucose but also led to the lowest levels of linolelaidic acid (21.47 ± 0.36%), α-linolenic acid (13.68 ± 0.32%), and nervonic acid (1.21 ± 0.00%). -Sucrose addition significantly increased the levels of arachidic acid (5.03 ± 0.23%), erucic acid (5.45 ± 0.22%), and docosadienoic acid (1.89 ± 0.10%). -Highest myristoleic acid (5.50±0.05%) from BSF larvae reared on fermented PKM with addition of maltose.

9.	Bokau & Witoko, (2017)	Fermented palm kernel cake (PKC) with commercial probiotics at different percentages 0%, 3%, 4% and 5%.	-The highest total (gram) of BSF larvae was 178.12g obtained from 0% probiotic treatment. Others, 172.61g, 79.09g and 14.06g obtained from fermented PKC at 3%, 4%, 5% respectively. These results indicated that the total biomass of BSF larvae not affected from fermentation in PKC substrate.	-Crude protein and fat parameters were significantly different among treatments. The crude protein content enhanced with an additional probiotic treatment: 45.8% to 56.5%. Lipid content decreased gradually from 25.9%, 23%, 20.9% and 18.94% with increasing probiotic treatment. -Fermentation treatment using 3% probiotic produced the highest and better total amino acid of 36.49%.
10.	Liew et al. (2022)	Fermented PKE with different volumes of *Rhizopus. oligosporus:* 0.1, 0.5, 1,2,3,4,5 ml.	-1.45g maximum BSF larvae total weight of biomass gained. Weight gain from control 1.08g.	-The highest protein yield: 44.5%. -The highest lipid yield: 24.7%. -Lauric acid the highest FAME approximately 47-53wt%. -The sum of saturated FAME ranged from 79-83wt%.
11.	Klüber et al. (2022)	Fermented pretreatment 7:3 mixtures of empty fruit bunch (EFB) and PKM with fungus *Bajerkandera adusta* (BAD).	-Final BSF larvae weight: 303.0mg (chicken feed), 187mg (BAD), 149.3mg (non-fermented reference). -Final BSF larvae length: 26.0mm (chicken feed), 22.6mm (BSD), 20.4mm (non-fermented reference). -BSF larvae fed on the BAD diet 25% heavier and shorter development time of 30 days.	-

RESULTS AND DISCUSSION

Description of Search Results

A total of 247 articles were identified through online searches in the databases of Web of Science, Scopus, PubMed, and Google Scholar. Fourteen duplicate studies, defined as identical records retrieved from the multiple databases used were removed. Additional 93 articles were excluded for not meeting the criteria of research articles, resulting in 140 articles remaining after the initial screening process (Figure 1). Subsequently, 128 articles were removed due to their titles and abstracts being unrelated to the focus of this review. In alignment with the objective of this review, only articles that utilized palm kernel by-product (PKB) namely palm kernel cake (PKC), palm kernel meal (PKM) and palm kernel expeller (PKE) as feed for BSF larvae were selected. Additionally, some articles that reported variations in feeding substrate preparation, such as mixing with other organic waste, fermentation with microorganisms, and supplementation with other substances were included for review. This resulted in a total of 12 articles being eligible for the quality assessment step. These articles underwent a comprehensive full-text reading process, and one was removed, as it failed to achieve at least 50% of the total score. Consequently, 11 articles were selected for the further review process. As detailed in Table 5, the impact of PKB substrate modification was identified on (i) BSF larvae growth and development and (ii) BSF larvae biomass nutritional profiling, thus considered as two primary themes in this review.

Effect of PKB on BSF Larvae Growth and Development

In this review, the terms unmodified and modified substrate are used as broader categories for consistency and clarity. Unmodified substrate refers to PKB, namely PKC, PKM, and PKE, used in their original form without any biological, chemical, or physical treatment, commonly referred to as single substrates. On the other hand, modified substrate refers to PKB that has undergone mixing with other substrates or pre-treatment, such as fermentation using microorganisms to enhance its nutritional value or biodegradability. These broader terms are used to streamline discussion across diverse studies, however, each specific substrate condition such as single, mixing, or fermented is clearly specified throughout the review.

A review of 11 articles revealed that only one study employed single substrates Binsin et al. (2023), one study utilized both single and mixing with other substrates (Rasdi et al. 2023) while the rest concentrated on modifying the substrate either by mixing with other substrates or fermenting with microorganisms. This trend suggests that modified substrates are more prevalent than unmodified ones, highlighting the versatility of PKB as a substrate in the BSF larvae bioconversion process.

Single Substrate

As outlined in Table 5, the studies that employed unmodified PKB were primarily focused on evaluating the substrate's potential without altering the properties of the substrates. In this case, the impact of the substrate on BSF larvae growth and development is the main aspect of the evaluation. Binsin et al. (2023) investigated four types of organic waste: PKE, food waste (FW), coconut endosperm (CE), and chicken manure (CM) without modification. PKE was simply mixed with water at a 1:2.5 ratio to achieve the desired moisture content, thereby preserving its physical, chemical, and biological characteristics. This approach provided valuable insights into how different types of organic waste influenced the performance of all BSF life stages. The study examined the performance of the BSF larvae, specifically looking at parameters such as larvae survivability and development time. Results indicated that PKE, while beneficial, did not perform as well as some other organic wastes. In terms of larval survivability, CM, FW, and CE achieved a 100% survival rate, whereas PKE recorded a slightly lower survival rate of 94%. This suggests that while PKE is a viable option, it may not be as effective as these other substrates in maximizing larval survivorship. However, PKE demonstrated a relatively shorter larval development time (16.87±0.05 days) compared to CE, while also providing competitive development rates similar to those achieved with FW. This observation aligns with the findings of Kinasih et al. (2018), which investigated the effects of three locally available plant-based organic wastes namely horse manure (HM), vegetable waste (VW), and tofu dreg (TD) on the growth performance of BSF larvae. Their finding demonstrated that all three substrates were suitable as feed sources for BSF larvae. However, variations in the physical characteristics and chemical compositions of the substrates significantly influenced larvae development time, harvested biomass, digestibility efficiency, and overall biomass conversion efficiency, with each substrate exhibiting distinct effects on the BSF larvae performance. Overall, while PKE is a useful substrate for BSF larvae, its performance in terms of survivability and development time suggests that it may benefit from modification or enhancement when compared to other organic wastes like CM and CE.

In another study, Rasdi et al. (2023) examined three different agricultural wastes such as PKE, soybean waste (SW), and coconut milk waste (CMW), to obtain direct data on the growth and development of BSF larvae. In the initial stage of the study, unmodified PKE, SW, and CMW were individually tested as feed substrates for BSF larvae. Similar to the findings by Binsin et al. (2023), BSF larvae performance was influenced by the substrate used, but this study emphasizing larval length and weight rather than survivability and development time. The results showed, the growth performance of BSF larvae varied significantly across the different substrate treatments. BSF larvae reared on PKE demonstrated superior development, achieving the highest mean length of 22.67mm and mean weight of 0.27g. In contrast, BSF larvae fed on CMW showed the poorest growth, with the lowest mean length of 18.33mm and mean weight of 0.15g. To explore further, the focus shifts from using unmodified substrate feed to modified substrate feed, specifically mixing substrate on different ration which might show promising potential for enhancing BSF larvae growth performance. Modification of the substrate through certain methods may offer significant improvements over its unmodified state, addressing limitations seen in previous studies.

Mixing Substrate

In a follow-up study by Rasdi et al. (2023), PKE and SW were further investigated due to their promising results in the initial research. To optimize the substrate composition, both substrates were mixed in various ratios. The mixture at a ratio 80:20 of SW to PKE recorded the highest BSF larvae length of 22.67mm and weight of 0.28g while the 20:80 ratio recorded the lowest BSF larvae length of 19.67mm and weight of 0.17g. Although there was increasing trend in BSF larvae mean length was observed with higher proportion of SW in the mixture, statistical analysis indicated that the BSF larave mean length was not significantly affected by the substrate ratio. In contrast, there was a statistically significant difference in BSF larvae mean weight across the different SW:PKE ratios. Interestingly, while PKE outperformed SW as a single substrate in the initial study, the results from this mixing substrate suggested that a higher proportion of SW in the mixture enhances BSF larvae growth performance. These findings indicate that although BSF larvae can grow well on both PKE and SW individually, their growth and development are slightly improved when both substrates are combined, highlighting the importance of substrate composition in BSF larvae rearing.

Study by Bajra et al. (2023) explored the effects of substrate modification on BSF larvae performance by preparing different feed treatments using varying proportions of PKM and oil palm empty fruit bunches (OPEFB). The purpose of such modifications was to alter the substrate properties and evaluate how different combinations influenced BSF larvae performance considering the parameters of larvae weight and survival rate. This approach was motivated by the need to improve the nutritional properties of PKM, which contains crude fibre and mannan, compounds that inhibit full nutrient utilization (Sathitkowitchai et al. 2018). Through these modifications, it is aimed to enhance the efficiency of PKM and other palm-based wastes in promoting BSF larvae growth performance. The findings indicated that different substrate compositions significantly impacted BSF larvae weight and survival rate. At the beginning of the experiment, five days old BSF larvae across all treatments exhibited similar weights, indicating no initial differences in growth potential. However, as feeding progressed, differences in BSF larvae growth became evident. By day 13, BSF larvae fed with PKM, and mixed substrates achieved significantly higher weights, ranging from 100 mg to 150 mg. In contrast, BSF larvae fed exclusively with OPEFB, whether coarse or fine, showed markedly slower growth, with final weights remaining below 50 mg. These trends reflect the nutritional limitations of OPEFB as a sole substrate. Regarding the survival rate, the best performance (96.67%) was observed in BSF larvae fed a mixture of 80% PKM and 20% fine OPEFB. Conversely, the lowest survival rate (56%) occurred in BSF larvae fed 100% coarse OPEFB. These findings confirm that while PKM supports robust larval development, OPEFB alone is inadequate, and mixing it with PKM is essential for improved BSF larvae growth and survivability.

Another study exploring substrate modification through mixing is the study by Raksasat et al. (2021). In this study, instead of mixing same category of waste, sewage sludge from wastewater treatment plant and PKE, palm kernel by-product was mixed at various ratios. The findings showed that the presence of PKE significantly improved BSF larvae growth performance, with BSF larvae weight increasing as the PKE content increased, reaching a maximum weight of 46.99 mg/larva at a 2:3 sewage sludge to PKE ratio. However, further increases in PKE content led to a drop in BSF larvae weight. Besides that, in the presence of PKE, the BSF larvae rearing duration is shorter as the amount of PKE increased. From the results, at a 5:0 ratio, rearing duration took 27 days while at 1:4 and 0:5 ratio where the proportion PKE the high only took 13 days. As reported in this study, although BSF larvae favoured the presence of PKE, exceeding the amount of PKE also can retard BSF larvae growth thus suggesting at a ratio 2:3 is the optimum ratio of sewage sludge to PKE for optimum BSF larvae growth. These findings also reflect those of Bajra et al. (2023), which investigated nine different combinations of PKM and OPEFB. Among the treatments, optimal results were achieved with a 50:50 mix of PKM and coarse OPEFB, yielding a survival rate of 87%. Although the highest survival rate (96.67%) was observed in BSF larvae fed with 80% PKM and 20% fine OPEFB, the study emphasized the importance of balanced substrate composition. Both studies highlight that while PKM or PKE significantly enhance BSF larvae performance, their proportion in the mixture must be optimized to prevent potential negative effects on larval growth.

Besides that, in the study conducted by Nugroho et al. (2023), seven treatments formulated from PKM, fish feed pellets (FFP) and various level of fructose were studied toward the effects as BSF larvae feed. The study revealed that BSF larvae fed with PKM, FFP, and the combinations with or without fructose supplementation exhibited increased BSF larvae weight but not significant changes in length. The addition of 10% fructose had the greatest impact on BSF larvae weight, resulting in the highest weight of 0.24±0.004g. In terms of BSF larvae length, although the length ranged from 18 mm to 20.5 mm across the different substrate treatments, statistical analysis indicated that fructose addition did not significantly affect the

BSF larvae length. Similarly, survival rates followed a comparable trend, ranging from 93.00 ± 0.70% to 97.00 ± 2.38%, with the highest survival observed in BSF larvae fed a PKM: FFP mixture supplemented with 7.5% fructose, and the lowest in those fed the PKM: FFP mixture without fructose. Despite these variations, the differences in survival rates were not statistically significant across treatments. These results highlight the potential of enhancing PKM based substrates with complementary nutrients to improve BSF larvae growth performance, although some parameters may not respond significantly to supplementation. The study also underscores the potential of PKM as a versatile substrate for BSF larvae, especially when combined with other nutritional sources such as FFP with high protein content, supporting the notion that modifying agricultural waste can contribute to more effective BSF larvae bioconversion process as waste management solution. These findings show that combining PKM with FFP and varying levels of fructose improves the substrate's nutritional profile. Crude protein increased from 15.19% in PKM and 16.32% in FFP to 16.38% in the PKM: FFP mix, peaking at 16.67% with 2.5% fructose. Higher fructose levels reduced protein to 16.11%, 15.58%, and 15.98% at 5%, 7.5%, and 10%, respectively. Conversely, carbohydrate content rose from 60.11% (PKM) and 61.89% (FFP) to 63.11% in the 10% fructose blend, reflecting the sugar's contribution.

Besides mixing, other method used to modify the substrate was fermentation. Through fermentation method, there were seven studies modified the substrates by applying different fermentation protocols including fermentation duration, types of products or microorganisms used, and amount of fermentation agent used. Nugroho et al. (2022) investigated the growth performance of BSF larvae using two types of fermented substrates, PKM and cow manure (CM). Both substrates were fermented with EM4 and sugar for four days and then used after a seven-day interval. The study found that BSF larvae fed on fermented CM performed better overall than BSF larvae fed on fermented PKM. The length of BSF larvae fed fermented CM reached 20 mm, compared to 18 to 18.5 mm for BSF larvae fed fermented PKM. Similarly, the weight of BSF larvae in the fermented CM group ranged from 0.195 to 0.2 g, whereas BSF larvae fed fermented PKM ranged from 0.18 to 0.185 g. Although there were differences in both growth parameters, the BSF larvae weight fed either fermented PKM or fermented CM has no significant difference, instead length of the BSF larvae was significantly affected by the type of substrate. Despite limited research on the use of livestock manure like CM in BSF larvae rearing, this study highlights its promising potential for bioconversion applications.

In a separate study, Damanik et al. (2024) focused on using a single fermented substrate, specifically PKM fermented over different fermentation durations. In this study, BSF larvaeperformance was evaluated by survival rates, development time to reach prepupal phase and growth rate. The findings revealed that all treatments achieved survival rates above 99.0%, with the 2-day fermented PKM showing the highest survival rate (99.88±0.44%), nearly matching that of chicken feed (100.00±0.00%). Additionally, BSF larvae fed on 2- and 3-day fermented PKM reached the prepupal phase faster, at 17.00±0.00 days to 17.60±1.34 days, respectively. In contrast, BSF larvae fed on 4-day fermented PKM and 4-day water-soaked PKM took significantly longer to develop, requiring 20.60±1.34 days to 23.60±1.34 days, respectively. These development times reflect a trend where shorter fermentation durations corresponded to higher growth rates, while longer fermentation periods led to slower growth. However, across the fermented PKM treatments, the growth rate was not significantly different. This suggests that fermentation duration plays a critical role in substrate modification, with extended fermentation potentially reducing nutrient content and thereby diminishing growth performance.

In another study by Nugroho et al. (2024), the addition of various sugar such as fructose, glucose, maltose and sucrose to fermented PKM was predicted to improve BSF larvae growth. The results indicated that BSF larvae exhibited variations in weight and length. The addition of sugars to the fermented PKM demonstrated an overall improvement in both weight and length of the larvae. Among the sugar types tested, glucose resulted in the highest BSF larvae weight (2.75g) and length (1.60cm). However, despite the observed improvements, the study reported that only the length parameter showed a statistically significant increase. Thus, the hypothesis that adding sugars to fermented PKM would fully enrich the substrate was not entirely supported. Additionally, Bokau and Witoko (2017) investigated the effects of varying levels of fermentation agents on the fermentation process of PKC. Fermented PKC with probiotic materials of 0%, 3%, 4% and 5% were applied under natural conditions, anticipating an increase in BSF larvae biomass. However, the findings indicated that fermentation did not enhance BSF larvae biomass production. In fact, the highest yield of 178.12g BSF larvae came from unfermented PKC whereas 172.61g, 79.09g and 14.06g BSF larvae obtained from substrate treatments of 3%, 4% and 5% fermented PKC respectively.

In a different approach, two separate studies have utilized fungal species as fermentation agents. Liew et al. (2022) pre-fermented PKE with different volumes of *Rhizopus oligosporus*, while Klüber et al. (2022) ferment a mix of 7:3 empty fruit bunch (EFB) and PKM with the fungus *Bajerkandera adusta* (BAD). Referring to the study by Liew et al. (2022), the effects of various fermented PKE is evaluated on the total weight of BSF larvae biomass gained. The results indicated, with fermented PKE with *R. oligosporus*, it improved the total weight of BSF larvae. As the inoculum volume of *R. oligosporus* increased, the total weight of BSF larvae also increased, with the highest weight gain of 1.45g at the optimal 0.5 ml inoculum. However, when the inoculum exceeded 0.5 ml, the weight gain declined by approximately 12% to 1.27g. Further increases in fungal inoculum volumes at 5ml, the weight gained by BSF larvae dropped drastically to 1.13g which was closed to the control. An almost similar trend was observed by Klüber et al. (2022) where BSF larvae fed a diet of EFB and PKM fermented with *B. adusta* (BAD) outperformed those fed with the non-fermented reference (NFR). The final BSF larvae weight and length differed significantly between diets with the largest and heaviest BSF larvae reared on the chicken feed (303.0mg, 26.0mm), followed by those reared on the BAD (487.0mg, 22.6mm). Additionally, larvae reared on the BAD diet had a shorter development time of 30 days, while those on the NFR diet took 41 days.

Effect of PKB Modification on BSF Larvae Nutritional Profiling

The modification of substrates in BSF larvae feed preparation was designed to enhance the nutritional profile of PKB through methods such as mixing or fermentation. Researchers are particularly interested in examining how these modifications influence the nutritional composition of BSF larvae, including changes in protein, lipid, and essential nutrient content. Understanding these effects is crucial for optimizing BSF larvae feed formulations to improve the overall quality and value of BSF larvae as a sustainable resource.

Mixing with other substrates is one of the primary methods employed to achieve this goal, as combining PKB with different feed ingredients optimizes nutrient content and boosts overall larval growth and development. Raksasat et al. (2021) investigated the effects of mixing sewage sludge with PKE on the lipid yield and fatty acid composition of BSF larvae. The study demonstrated that increasing the proportion of PKE initially enhanced lipid yield peaking (17±1.77%) with sewage sludge to PKE ratio of 3:2, before declining with further additions of PKE. Regarding fatty acid methyl ester (FAME) composition, the highest percentage component was lauric acid. The lauric acid content in BSF larvae increased with higher proportions of PKE in the substrate, reaching a peak at a sewage sludge to PKE ratio of 3:2. At this point, the lauric acid content rose to 53.36%, compared to 16.92% in the control contained PKE only. The trend showed a progressive increase with PKE addition, 19.56% at a 5:0 ratio, 24.28% at a 4:1 ratio, and 53.36% at a 3:2 ratio. However, further increases in PKE proportion led to a decline in lauric acid content, dropping to 21.37% at a 2:3 ratio and 7.91% at a 1:4 ratio. In contrast, oleic acid content consistently declined as the proportion of PKE in the substrate increased. The highest oleic acid level, 24.37%, was observed at a 5:0 ratio. This decreased to 20.29% at a 4:1 ratio, 9.22% at a 3:2 ratio, and 5.00% at a 2:3 ratio. This study concludes that the balance of feed components plays a crucial role, as the addition of PKE enhanced BSF larvae final weight, which in turn influenced lipid yield and the FAME profile. Therefore, based on the study, the optimum sewage sludge to PKE ratio of 3:2 produced the highest lipid yield and a favourable fatty acid composition that contributed to good quality biodiesel.

While Raksasat et al. (2021) primarily concentrated on lipid yield and fatty acid composition specifically for biodiesel production, Nugroho et al. (2022) took a broader approach by examining both the nutritional composition and fatty acid profiles of BSF larvae fed with fermented PKM and fermented CM. BSF larvae fed with the fermented PKM demonstrated relatively higher crude protein content (47.34±0.04%) compared to those fed with CM (46.64±0.04%). However, the crude lipid content was slightly lower (4.31±0.02%) in the fermented PKM-fed larvae versus those fed fermented CM (4.47±0.02%). Regarding the fatty acid profiles, notable differences were observed between the two diets. BSF larvae reared on fermented PKM showed higher levels lauric acid (29.27%) and heptadecanoic acid (22.10%). In contrast, BSF larvae fed with fermented CM exhibited higher levels of myristoleic acid, palmitoleic acid, linolenic acid, and arachidic acid. These findings highlight how the type of substrate can influence both the proximate composition and the fatty acid profiles of BSF larvae.

In another study, Nugroho et al. (2023) expanded their research by examining the effects of supplementing PKM with fish pellets and fructose on the nutritive value and fatty acid profiles of BSF larvae. Their study found that, FFP substrate treatment led to high crude protein content of 55.68±2.30%. Across substrate treatments with added various fructose (2.5%, 5%, 7.5% and 10%) to PKM: FFP, the crude protein contents were not significantly different, 50.23±1.33%, 50.02±0.25%, 49.58±1.01% and 51.88±0.22% respectively. Besides that, the supplementation of fructose was found to reduce the crude fat of BSF larvae. However, for the substrate mixture of PKM: FFP, the crude fat was the highest (7.69±0.04%). In term of fatty acid composition, similar with the findings of Raksasat et al. (2021), lauric acid was the dominant fatty acid. However, this study revealed that increasing fructose supplementation in the PKM: FFP mixture led to the declined in lauric acid content, with the lowest value recorded at 11.22 ± 0.02% in the PKM: FFP 10% treatment. Interestingly, the study also demonstrated that BSF larvae were able to biosynthesize high levels of palmitoleic acid, with concentrations exceeding 15% of the total fatty acids in some treatments.

Nugroho et al. (2024) expanded their research by evaluating fermented PKM addition with 5% of various sugars as a feed substrate for BSF larvae. The type of sugar added significantly influenced both the crude protein content and fatty acid profile of the BSF larvae. BSF larvae reared on fermented PKM with fructose showed the highest crude protein content (52.26 ± 0.29%), while those reared on PKM with maltose had the lowest (49.35 ± 0.48%). In terms of fatty acids, glucose addition resulted in the highest level of lauric acid (22.60 ± 0.34%) but also led to the lowest levels of linolelaidic acid (21.47 ± 0.36%), α-linolenic acid (13.68 ± 0.32%), and nervonic acid (1.21 ± 0.00%). Sucrose addition significantly increased the levels of arachidic acid (5.03 ± 0.23%), erucic acid (5.45 ± 0.22%), and docosadienoic acid (1.89 ± 0.10%). Furthermore, the highest concentration of myristoleic acid (5.50 ± 0.22%) was found in BSF larvae reared on fermented PKM addition with 5% maltose. These results highlight that the type of sugar added can significantly alter the nutritional composition of BSF larvae, particularly the crude protein and fatty acid profiles.

Other than mixing with other substrates, fermentation is a method used to enhance the nutritional value of BSF larvae feed by incorporating beneficial microbes into substrates like PKB. This process involves the introduction of specific microbial cultures, which help break down complex compounds into more digestible forms. The fermentation process not only improves the digestibility of the feed but also enriches its nutrient profile, leading to higher levels of protein, lipids, and essential nutrients in the larvae. In the study by Bokau and Witoko (2017), fermentation of PKC significantly enhanced the crude protein content (45.8 to 56.5%) of BSF larvae biomass with an additional probiotic treatment but did not significantly improve the lipid content. Lipid content decreased gradually from 25.9%, 23%, 20.9% and 18.94% with increasing probiotic treatment. Fermentation also influenced the amino acid profile of BSF larvae, with the 3% probiotic treatment showing a significantly higher total amino acid profile (36.49%). These findings suggest that the addition of probiotic concentration improves the nutritional profile of PKC, particularly in terms of protein content and quality, but not in lipid production.

In the study by Liew et al. (2022), fermentation of PKE with *R. oligosporus* significantly enhanced both BSF larvae protein and lipid yield. Protein yield increased from 38.2% to 44.5%, the highest observed when the inoculation volume of *R. oligosporus* was increased from 0 to 0.5ml. A similar trend was seen in the lipid yield, which increased from 18.6% to a peak of 24.7%. However, further increasing the inoculation volume beyond 0.5ml of *R. oligosporus,* led to slightly declines in both protein and lipid yield. Besides that, for FAME profile particularly lauric acid was the highest across the controlled PKE, 0.5ml and 1.0ml of *R. oligosporus* inoculation treatments, ranging from approximately 47 to 53 wt%. Then, it was followed by myristic acid, palmitic acid and oleic acid. The sum of saturated FAME ranged from 79–83 wt%, making the BSF larvae-derived biodiesel highly oxidatively stable. Notably, the resulting BSF larvae biodiesel met the European EN 14214 specification, with polyunsaturated FAME content below 1% and linolenic acid methyl ester ranging from 2.17% to 4.02%, well under the maximum limit of 12%. According to Lanjekar and Deshmukh (2016), key indicators of FAME quality in biodiesel include oxides of nitrogen (NOx) emissions, oxidative stability, and cold flow properties, all of which are strongly influenced by fatty acid composition. Based on these results, the optimal inoculation volume was determined to be 0.5 mL, as it resulted in a 16.5% increase in protein yield, a 32.8% increase in lipid yield, and a 34.2% gain in biomass. Despite the positive effects of PKE fermentation, the resulting BSF larvae biomass exhibited nearly double the protein content compared to lipid, indicating that fermented PKE may be more suitable for applications targeting high-protein production rather than lipid accumulation for biodiesel.

CONCLUSION

Palm kernel by-product (PKB) can be utilized as a feeding substrate for Black Soldier Fly larvae (BSF) in the bioconversion process even without modification. However, our review shows that modified PKB whether mixed with other substrate types or fermentation, holds greater potential. As the BSF larvae feed on modified PKB, larvae growth and development improve and enhanced the conversion of PKB into larvae biomass that rich in protein or lipid.

Therefore, utilizing PKB in BSF larvae bioconversion is a promising sustainable PKB waste management and a more depth understanding of how it can be applied, how it affects the bioconversion process and how to improve biomass produced are worth exploring. This highlights PKB's value in sustainable waste management and its effectiveness in producing high-quality biomass for animal feed and other applications. Nonetheless, further research is needed to address several gaps, including effects of PKB utilization on post-feeding stages of BSF, the identification of alternative microbial fermenters to enhance the nutritional value of PKB, the impact of modified PKB on larval fatty acid profile as well as metabolic pathways involve as well as evaluating the scalability and cost-effectiveness of using modified PKB in large-scale BSF larvae production systems. These future directions will be critical to unlocking the full potential of PKB in sustainable biomass production for animal feed and other applications.

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No ethical issue is required for this research.

Data Availability Statements
This systematic literature review is based on previously published literature. All data used are publicly available and cited in the reference list.

Author's Contributions
All authors contributed ideas and were involved in drafting this systematic literature review, including the conceptualization, development of the search strategy, literature screening and data extraction. All authors also contributed to writing and revising the manuscript.

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