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Regional Case Study

Mapping the Potential of Organic Waste as a Bioconversion Substrate for Black Soldier Fly Larvae (BSFL) in Surabaya City and Sidoarjo Regency

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Abstract

Waste management remains a critical challenge in Indonesia, particularly in urban areas. Bioconversion using Black Soldier Fly Larvae (BSFL) presents a sustainable solution for transforming organic waste into high-value biomass rich in protein and fat. The objective of this study was to investigate the potential utilization of organic waste from markets, bakeries, and rejected products from the food and beverage (F&B) industry (specifically creamer and milk), as BSFL substrates, while mapping the existing bioconversion sites. Data was collected through interviews, observations, and field measurements. Primary data included location details, technical specifications, implementation constraints, and BSFL bioconversion sites. Waste composition was analyzed via Loud Count Analysis during a 4-day sampling period. This research was conducted in Surabaya City and its surroundings. The results indicate that market waste mostly consists of dark green vegetables (26.5%), other vegetables (64.1%), and year-round fruits (53.9%). Furthermore, the daily average rejected bread is 2.6-2.7 kg. Rejected foods and beverages include creamers, liquids, and sweetened condensed milk. The facility processes 16.16 tons/day of substrate potential, producing 44.61 tons fresh larvae and 53.85 tons frass, with profits of IDR 58.1-969.6 million. The findings demonstrate significant potential for utilizing local organic waste as BSFL substrates in the study area.

Keywords: Bakery waste; bioconversion; Black Soldier Fly; market waste; rejected products

1. Introduction

Waste disposal remains a contentious topic in Indonesia. According to the National Waste Management Information System (SIPSN) data (2024), 54.3% of the total waste comprises of household waste, followed by market waste at 13.46% (Ministry of Environment, 2024), which consists of 51.99% organic waste. A high proportion of organic waste presents opportunities for energy recovery through the implementation of appropriate processing methods. Waste management techniques, such as landfilling, composting, recycling, mechanical-biological treatment, and waste-to-energy (WTE) treatment, are commonly applied (Psomopoulos et al., 2009). However, since current waste treatment strategies primarily rely on end-of-pipe solutions, the accumulation of materials in landfills and release of emissions into the environment is inevitable (Chioatto et al., 2023). Sustainable waste management strategies have been implemented to partially mitigate these issues, one of which involves using black soldier fly larvae (BSFL) as agents for decomposing organic waste.

In recent years, BSFL have gained attention because of their ability to bioconvert organic waste into livestock feed and fertile compost (Fischer et al., 2021; Gao et al., 2019). These larvae consume organic waste and convert it into protein- and fat- rich biomass (Bohm et al., 2022). Biomass can be used as a feed for poultry, fish, pigs, and other animals (Cardinaletti et al., 2019; Hartinger et al., 2022; Marie Håkenåsen et al., 2021). The organic waste consumed by BSFL can come from various types of waste, including food waste, expired milk, outdated bread, and vegetable waste (Borel et al., 2021; Sari et al., 2023; Song et al., 2021). Additionally, they can effectively convert fruit waste and mixed sludge waste into nutrient-rich biomass (Mishra & Suthar, 2023).

Organic waste from markets, leftover bread from bakeries, and industrial rejected products, also have potential as food substrates for BSFL production. These waste sources are predominantly located in the surrounding environment, with notable concentrations in the Surabaya area and its vicinity. It is essential to identify the potential of organic waste sources as a feedstock for bioconversion substrate utilization via BSFL. Focusing on the market's organic waste involves mapping the waste of fruits and vegetables as a nutrient-rich source of fiber, minerals, and protein for BSFL. Carbohydrate and protein sources are obtained from the bakery and rejected products from Food and Beverage (F&B) Industry. Current literature lacks detail regarding the characterization of fruit and vegetable waste composition, as well as the bioconversion potential of bakery and creamer industry byproducts. Therefore, this study will systematically evaluate the suitability of these organic waste streams as black soldier fly larvae BSFL substrates, while concurrently assessing the production potential of larval biomass and frass.

2. Methods

This study's mapping encompasses two distinct types: mapping potential substrate for BSFL bioconversion and identifying the locations where bioconversion is applied. This study focuses on Surabaya and the surrounding regions, with a particular emphasis on Sidoarjo Regency. The targets for the potential substrate mapping included traditional markets, bakeries, and the creamer and dairy industries. The data collected comprised primary and secondary data.

2.1. Materials

The materials required for this study include stationery and sampling equipment, including digital hanging scales, trash bags, plastic bags, and personal protective equipment (gloves and masks). The equipment was deployed while compiling fruit and vegetable waste in traditional markets. In addition to taking direct measurements, this study conducted interviews, meaning stationery was required to complete the questionnaire.

2.2. Data Collection

The data collection methods consisted of direct interviews, field observations, and/or field measurements. The primary data comprised general information (location and address), technical and technological data, and additional data such as constraints and information on other locations where BSFL bioconversion was implemented. The technical-technological data were divided into two categories corresponding to the two mapping types. The data gathered for substrate mapping include details on waste composition, waste generation (specifically in bakeries), waste disposal patterns, and frequency. The location mapping of bioconversion application involves factors such as processing capacity, substrate source composition, substrate treatment, feeding and stirring frequency, sales flow and product form, harvest quantity, harvest timing, and site-specific constraints. Traditional market waste compositions exclusively focus on fruit and vegetable waste. The waste composition measurement was conducted using the *Loud Count Analysis* method over four consecutive days, in accordance with the Indonesian National Standard SNI 19-3964-1994 (National Standardization Agency of Indonesia, 1994). The composite waste analyzed consisted exclusively of fruit and vegetable waste, which was further categorized by type. The quantification of fruit and vegetable waste was comprehensive, encompassing all organic waste generated within a 24-hour period without any predetermined limits. The secondary data information was collected from relevant agencies and departments that have implemented waste management using BSFL bioconversion. Moreover, other secondary data is also compiled through literature reviews of articles and journals.

2.3. Determination of Number and Sampling Location

This study employed a quantitative research approach, in which numerical data were systematically analyzed using both statistical and descriptive methods (Abdullah et al., 2022). In accordance with established standards for quantitative research, a minimum sample size of 30 was adopted (Kerlinger & Howard B. Lee, 2000). The minimum sample size was determined through application of the Slovin formula (Sugiyono, 2011), expressed as following equation (1):

$$n = \frac{N}{1+N(e)^2} \quad (1)$$

Where:

n = sample size/number of respondents

N = population size

e = the permissible margin of error for sampling accuracy that remains acceptable.

Given the relatively small population size in this study (<100), an e value of 20% was adopted, following Sugiyono (2011). The selection of markets in Surabaya was determined based on market conditions and the population density of the sub-districts in which they are situated. Surabaya comprises 67 markets, categorized as 6 in good condition, 51 in moderate condition, and 10 in sufficient condition (Table 1). Furthermore, the population density of sub-districts in Surabaya was classified into four tiers: very high, high, medium, and low. The density distribution revealed 2 sub-districts with very high density, 5 with high density, 8 with medium density, and 16 with low density. The N value was derived from markets in moderate and good condition located in sub-districts with medium density or higher, resulting in N = 18 (comprising 2 markets in medium-density areas, 4 in very-high-density areas, and 12 in high-density areas). Consequently, the sample size (n) was determined to be 10.

Table 1. Market condition category

Density category	Number of sub-districts	Market category		
		Good	Medium	Simply
Low	16	0	12	4
Medium	8	2	24	2
High	5	0	12	3
Very high	2	4	3	1
Total	31	6	51	10

The selection of market samples in Sidoarjo was conducted based on market size categorization, determined by the number of stalls, with a focus on small-scale markets for representation. Market size classification followed the criteria established by Pratama & Hertati (2021). Consequently, medium and large-sized markets were sourced from Surabaya City, while small-sized markets were selected from Sidoarjo Regency. The surveyed markets were chosen based on their type, excluding specialized markets (e.g., flea markets) and prioritizing those specializing in fruits and vegetables. This selection criterion was implemented because the study's assessment of organic waste composition in traditional markets was restricted to fruit and vegetable waste. In Sidoarjo District, the population size (N) was determined to be 3, resulting in a sample size (n) of 3, selected from sub-districts with medium to very high population density.

The sample sizes for bakeries, dairy industries (milk and creamer production facilities), and BSF bioconversion implementation sites could not be established a priori due to the unavailability of complete population data. Consequently, all identified locations of these three categories were initially compiled, and survey permissions were sought for each documented site. Location data were acquired through online sources and supplementary information gathered during preliminary interviews. Site surveys were ultimately conducted only upon receiving explicit authorization from the respective property owners or management.

This research aims to identify market quantity and locations by examining their spatial distribution, regulatory compliance, and proximity metrics. The findings include a geospatial map illustrating the identified locations, a detailed composition analysis of fruit and vegetable substrates, and an estimated potential yield of BSFL products derived from the assessed substrate availability.

2.4. Calculation

This study conducted a comprehensive economic analysis encompassing investment costs, operational and maintenance (O&M) expenditures, and projected revenue streams. These financial parameters serve as critical inputs for assessing the venture's economic viability and profitability. Net profitability was determined through differential analysis between total anticipated revenues and aggregate O&M costs. To account for product market variability, profitability projections were modeled under two distinct commercialization scenarios: (1) sales of fresh (wet) larvae and (2) sales of processed dry larvae.

3. Results and Discussion

A total of 50 locations were sampled, including 14 traditional markets, 24 factory and bakery shops, 3 industries, and 9 BSFL bioconversion application sites. The locations are illustrated in Figure 1.

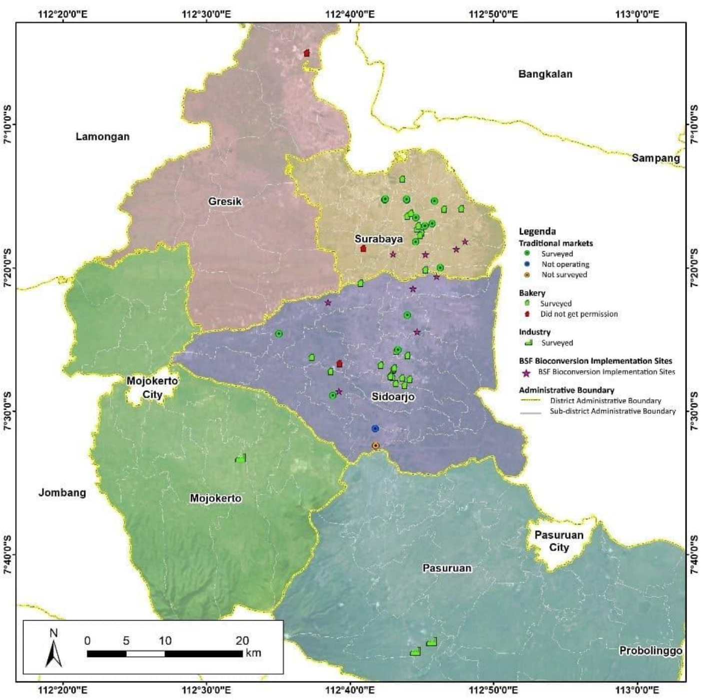

Figure 1. Mapping location distribution

3.1. Mapping of Organic Waste from Traditional Markets

A total of 10 markets in Surabaya City and 4 markets in Sidoarjo Regency were surveyed. Waste collection was conducted once daily at five participating markets. Additionally, four markets reported a collection frequency of twice per day, while five markets conducted waste collection three or more times daily. Waste is disposed of in containers that can be sourced from the market environment or at the nearest temporary waste storage site (TPS) facilities. The technical information for each market surveyed is detailed in Table 2. Vegetable waste was classified into five categories in accordance with the MyPyramids system (Marcoe et al., 2006; Pennington & Fisher, 2009). The classification of vegetable waste is summarized in Table 3, and its composition is shown in Figure 2.

Table 2. Technical information of surveyed markets

Name of Market	City/region	Waste Disposal Location	Frequency of waste collection
Fruits market A	Surabaya	Containers in the market, with fruit waste sold to collectors	Once a day
Traditional market B	Surabaya	TPS Bogen	Once a day
Traditional market C	Surabaya	Containers in the market	Twice a day
Traditional market D	Surabaya	Containers in the market and sending to composting area in Kebun Bibit	Four times a day
Traditional market E	Surabaya	Containers in the market	Once a day
Traditional market F	Surabaya	Containers in the market	2-3 times a day
Traditional market G	Surabaya	Containers in the market	Organic every 3 days, inorganic every day
Surabaya Main market	Surabaya	Containers in the market	2-3 times a day
Fruits market H	Surabaya	Containers in the market	3-4 times a day
Sidotopo Main market	Surabaya	Containers in the market	Twice a day
Traditional market I	Sidoarjo	Containers in the market	Twice a day
Traditional market J	Sidoarjo	Containers in the market	Twice a day
Traditional market K	Sidoarjo	Containers in the market	Three times a day
Traditional market L	Sidoarjo	Containers in the market	Once a day

Table 3. Classification of vegetables

Classification	Example
Dark green vegetables	Pokcoy, broccoli, mustard greens, dark green leafy lettuce, kale, mesclun, mustard greens, romaine, spinach, chard, and watercress
Orange vegetables	Pumpkin seeds, butternut squash, carrots, hubbard squash, pumpkins, winter squash, and sweet potatoes
Dried beans and peas	Black beans, black-eyed peas, garbanzo beans (chickpeas), kidney beans, lentils, lima beans (cooked), cowpeas, dark red beans, pinto beans, soybeans, peas, tofu (tofu made from soybeans), and white beans
Starchy vegetables	Corn, green beans, lima beans (green), and potatoes

Classification	Example
Other vegetables	Artichokes, asparagus, bean sprouts, beets, Brussels sprouts, cabbage, cauliflower, celery, cucumbers, eggplant, chickpeas, green or red peppers, lettuce, mushrooms, okra, onions, parsnips, summer squash, tomatoes, tomato juice, vegetable juice, turnips, wax beans, and zucchini

The survey findings reveal that several vegetables are absent from the table, necessitating a categorization of these vegetables into a specific group. The vegetables in question comprise chayote, young jackfruit, breadfruit, lemongrass, ohyong, kenikir, cassava leaves, and papaya leaves. Ohyong, kenikir, cassava leaves, and papaya leaves are classified as dark green vegetables. Chayote and lemongrass are classified as other vegetables. Young jackfruit and breadfruit are classified as starchy vegetables.

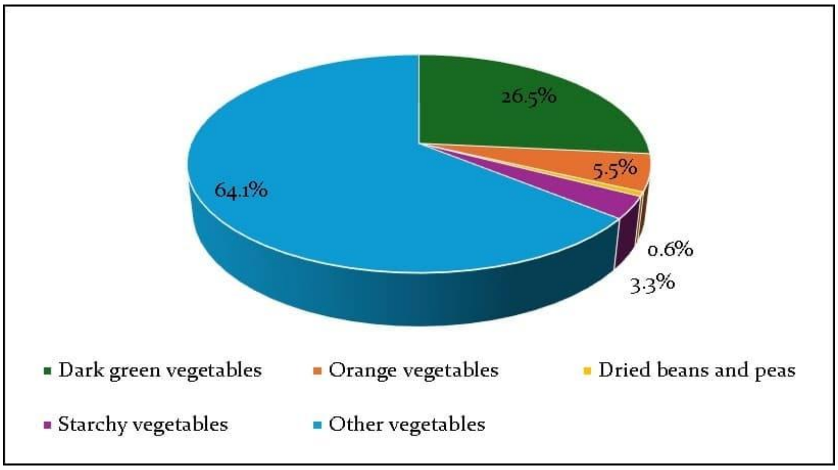

Figure 2. Composition of vegetable waste in surveyed markets

The findings reveal that within the Surabaya and Sidoarjo regions, the "other vegetables" category constitutes the largest share of market vegetable waste at 58.2%, followed by dark green vegetables at 32.9%. Therefore, the recommended substrate source is vegetable waste, which is most readily available in the market (dark green vegetables). Both dark green vegetables and legumes are considered suitable substrates for BSFL. Legumes are particularly notable for their high protein content, containing approximately 8 grams of protein per 0.5 cup serving. Among these, long bean seeds exhibit a protein concentration ranging from 27% to 31% (Nor Azmah et al., 2023), surpassing other vegetable types in protein content. The protein level in the bioconversion substrate plays a crucial role in determining both the protein composition and growth rate of BSFL (Beniers & Graham, 2019; Fuso et al., 2021).

Vegetable waste constitutes the predominant organic waste fraction across surveyed markets in Surabaya and Sidoarjo. Quantitative analysis revealed substantial variation in vegetable waste composition among markets: Soponyono (78%), Keputran (91%), Genteng (36%), Krian Baru (59%), Krian (76%), and Sepanjang (61%) (Al-Hanniya et al., 2022; Dhia Khairullah Risky et al., 2022; Muhamad, 2014; Triyanto, 2023; Waddin & Bagastyo, 2016). These findings highlight the significant potential of market-derived vegetable waste as a substrate for black soldier fly larvae (BSFL) bioconversion systems. Furthermore, valorization of this waste stream offers dual benefits: (1) provision of high-quality bioconversion feedstock and (2) enhanced waste reduction capacity in municipal public facilities.

Fruits were classified into two groups based on their fruiting season: perennial fruits, which are available throughout the year, and seasonal fruits. The categories are detailed in Table 4.

Table 4. Classification of fruits by harvest period

Group	Fruit type
Year-round Fruit	banana, pineapple, papaya, guava, guava, orange, grape, apple, melon, watermelon, salak
Seasonal Fruit	durian, mango, rambutan, duku, mangosteen, dragon fruit, avocado, jackfruit, ambarella fruit, soursop, strawberry, pear, star fruit, jicama, srikaya, passion fruit

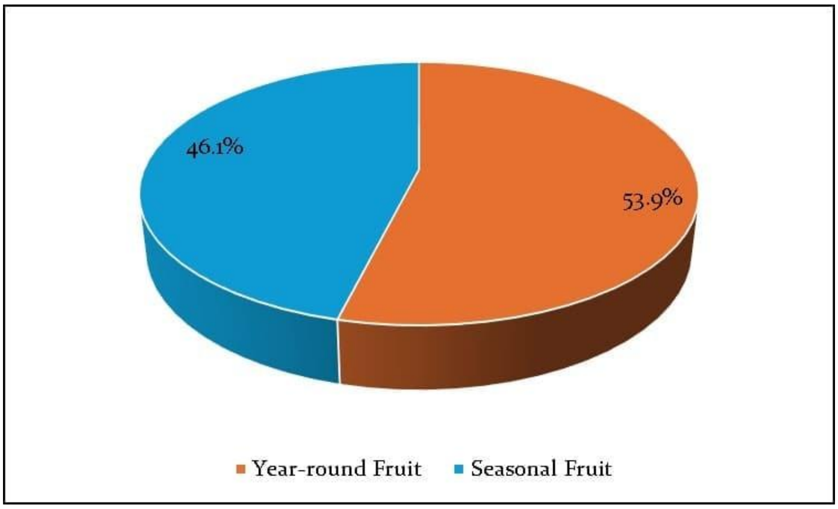

Figure 3. Fruit waste composition in surveyed markets

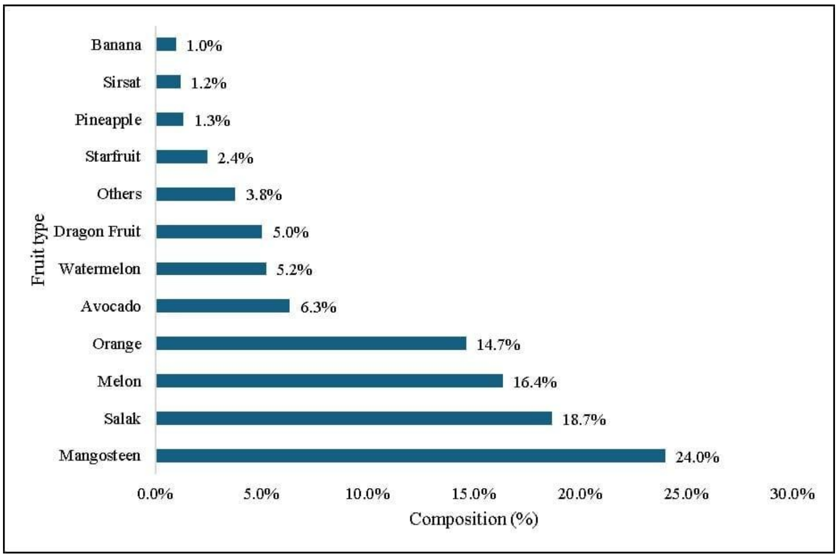

Figure 4. Fruit composition by type in surveyed markets

Year-round fruits dominate the market fruit waste stream, accounting for 53.9% of the total. As illustrated in Figure 4, mangosteen and salak are the predominant contributors, accounting for 24% and 18.7% of fruit waste, respectively. Market surveys in Surabaya and Sidoarjo revealed variable fruit waste composition across different locations: Pacar Keling Market (51%), Genteng Market (23%), Krian Baru Market (14%), Sepanjang Market (14%), and Krian Market (6%) (Al-Hanniya et al., 2022; Dhia Khairullah Risky et al., 2022; Muhamad, 2014; Triyanto, 2023; Waddin & Bagastyo, 2016). These substantial quantities of fruit waste demonstrate considerable potential as feedstock for BSFL bioconversion systems. The heterogeneous distribution of fruit waste among markets suggests the need for location-specific valorization strategies to optimize organic waste utilization through insect-based bioremediation. The amount of water in specific types of fruit must also be considered, as the ideal moisture level for bioconversion is approximately 70% (Alvarez, 2012). Accordingly, it is advisable that year-round fruits with relatively low moisture content should be prioritized as substrates for BSFL bioconversion.

Vegetable and fruit waste can be utilized as breeding substrates for the mass production of BSF larvae. Several studies have investigated the suitability of specific types of fruits as BSFL substrates. Fuso et al. (2021) employed exotic fruits such as apple, kiwi, pineapple, and melon in BSFL bioconversion, achieving prepupal protein contents ranging from 35% to 42%. Similarly, Scala et al. (2020) demonstrated the potential of apples and bananas as effective substrates. Larvae reared on apple and banana substrates had daily average weights of 1.54 and 1.6 g/10 larvae, crude protein contents of 31.1% and 36.5%, and crude lipid contents of 36.1% and 27.9%, respectively. Furthermore, Isibika et al. (2021) observed that orange peels could support larvae development up to 50.9 mg/larvae, with weight increasing to 93.9 mg/larvae when supplemented with banana peel.

The types of waste have an impact on larval growth. The fastest larval growth rate was observed in larvae fed with fruit waste at a weight of 25 grams (0.52 ± 0.02 grams per day). This represented at least a 50% increase in growth compared to larvae fed with a palm decanter, as reported in Leong et al. (2016). Significant survival rates were noted on diets consisting of fruits such as apples, pears, and oranges; vegetables like lettuce, green beans, and cabbage; and mixed combinations thereof, with recorded values ranging from 88.67% ± 6.12 to 96.44% ± 2.62 (Jucker et al., 2017). Experimental data from Jucker et al. (2017) demonstrate significant variation in larval biomass yields across different organic substrates: fruit waste produced 58 ± 0.003 mg/larvae, vegetable matter yielded 61.3 ± 0.00015 mg/larvae, while mixed fruit-vegetable substrates generated 51.3 ± 0.001 mg/larvae ($p < 0.05$). These findings establish a clear substrate-dependent growth response in BSFL, directly correlated with nutritional composition (carbohydrate-protein-lipid profile). Comparative analysis reveals that nutrient-dense composite substrates (vegetables/fruits/bread/brewery byproducts) can enhance larval biomass production up to 162.11 ± 2.22 mg/larvae ($p < 0.01$) (Arabzadeh et al., 2022), underscoring the critical role of substrate optimization in bioconversion systems. BSFL reared on fruit and vegetable substrates can achieve greater mean larval weight than those raised on food waste, albeit at the cost of requiring a longer cultivation period (Lalander et al., 2019). A diet lacking essential nutrients, particularly proteins and carbs, may result in a prolonged duration of insect larvae consumption to make up for the nutritional deficiency (Banks et al., 2014; Simpson et al., 2006). In order to boost the mean larval weight and reduce cultivation time, it is suggested that fruit and vegetable substrate be blended with other organic waste to offer a broader range of nutrients for larval growth.

3.2. Mapping of Rejected Products from Bakery and Food and Beverage (F&B) Industry

The survey was conducted at 9 bakeries in Surabaya and 15 in Sidoarjo. Technical data were collected in terms of bread waste generation and disposal practices. Results showed that 41.7% of bakeries reported no bread rejection because unsold bread can be sold at a reduced price or distributed for free. In contrast, the other 58.3% of bakeries generated bread waste, with an average of 2.6–2.7 kg per day. The total amount of rejected bread produced is 37.8 kg per day. Of the bread waste generated, 50% was sent or sold to third-party companies, 28.6% was disposed of at the TPS facilities and 21.4% was returned to the main factory. Rejected bread consists of various types, including white bread crusts, white bread, sweet bread, donuts, and bread with various fillings.

Bread waste has been previously studied as a potential substrate for BSFL. Fischer et al. (2021) reported that donut-based substrates yielded 54.35 grams of larvae and prepupae. These larvae contained 54% protein and 47% fat, whereas prepupae contained approximately 68% protein and 43% fat. Similarly, a study by Ewald et al. (2020) found that larvae reared on bakery waste have an average weight of 137 milligrams, with 39.2% crude protein and 57.8% crude fat.

Feeding BSFL with 100% expired bread yields a survival rate of 101%, which is likely to decline even further when supplemented with Aquaculture waste, as indicated by (Lopes et al., 2020). Compared to the addition of Aquaculture waste, it has the shortest rearing time at 12 days, yet yields larvae with a final weight of only 100 mg. The substrate achieved a biomass conversion ratio (BCR) of 23.9% and a material reduction of 62.9%. Feeding the larvae a diet of 100% bread will lead to a decrease in their protein content. A balanced diet consisting of protein, fat, and carbohydrates is crucial for achieving optimal insect development, including growth rate and metamorphosis speed, as well as weight gain (Danieli et al., 2019). Consequently, BSFL growth is more successful when provided with rejected bread mixed with other organic waste.

The food and beverage industry survey was limited to the creamer and dairy sectors, as these industries generate rejected products that remain nutritionally viable and suitable for BSFL cultivation. A creamer facility and two dairy industry sites in the regions around Surabaya were surveyed. The rejected creamer may originate from the production, storage, and quality control testing processes. During production, products that fail to meet quality standards related to color, particle dimensions, and flavor are rejected. During storage, rejection results from damaged packaging, such as punctures or tears. Quality control rejection includes leftover samples from analytical procedures or samples accidentally spilled during testing. Although the volume of rejected creamer is inconsistent and does not occur daily, a certain amount of waste is generated each month. Currently, this waste is managed by transferring it to a partner organization as one of the animal feed ingredients.

Rejected products from the dairy industry may include liquid and sweetened condensed milk. Rejected liquid milk is typically treated at a wastewater treatment facility, whereas sweetened condensed milk is handled by third-party processors. Among them, liquid milk is a suitable BSFL substrate, whereas sweetened condensed milk is generally not recommended due to its viscous texture and high sugar content. Liquid milk can be used as an extra component of the substrate and to control the moisture content of the substrate.

The incorporation of expired milk into larval feed has been shown to enhance growth performance and improve the Waste Reduction Index (WRI) and Efficiency of Conversion of Digested feed (ECD) value (Fitriana et al., 2025; Sari et al., 2023). According to Fitriana et al. (2025), the supplementation of expired milk resulted in a 2.7% increase in mean larval weight compared to the control group. Furthermore, research by (Sari et al., 2023)demonstrated that expired milk supplementation led to a 3.2% and 20.2% improvement in WRI and ECD, respectively, relative to unsupplemented feed. This enhancement can be attributed to the additional nutrients provided by expired milk, including carbohydrates, proteins, and lipids, which contribute to larval metabolic and developmental processes (Fitriana et al., 2025).

The compositional analysis reveals that non-dairy creamer (NDC) possesses potential as a supplementary ingredient in animal feed formulations. With a nutritional profile consisting of 3.02% protein and 5.86% lipid content, NDC can serve as a lipid source in feed, although excessive inclusion may yield adverse effects (Sun & Kim, 2018). While NDC can function as a viable substrate for BSFL, its incorporation requires careful dosage optimization. An optimal inclusion rate of 40%, beyond which progressive increments in NDC content demonstrate inhibitory effects on larval growth performance (Fitriana et al., 2025).

3.3. Mapping of BSFL Bioconversion Application Sites

There are 9 locations that utilize BSF bioconversion for waste processing, comprising 4 sites in the formal sector operated by the Surabaya City Government, 3 sites in the formal sector managed by village governments in Sidoarjo, and 2 additional locations in the informal sector owned by residents. Furthermore, two sites have ceased operations because of the Covid-19 pandemic. The waste being managed consists of food waste, as well as fruit and vegetable waste, originating from nearby households and nearby public establishments, such as markets and restaurants. The municipal government-owned formal sector does not engage in buying and selling BSF products, resulting in the larvae being provided to residents or utilized as fish and chicken feed. Wet larvae and egg products from other sectors are sold to their cooperative partners and to residents. Harvest duration typically spans 10-12 days, during which the waste is shredded and some areas are further ground by a specific machine. In general, the larvae are fed once every 4 days, with stirring taking place at the time of feeding. The biggest obstacle in processing waste with this method is air pollution in the form of unpleasant odors coming from the processed waste. The source of waste for each location can be mapped as shown in Figure 5 below.

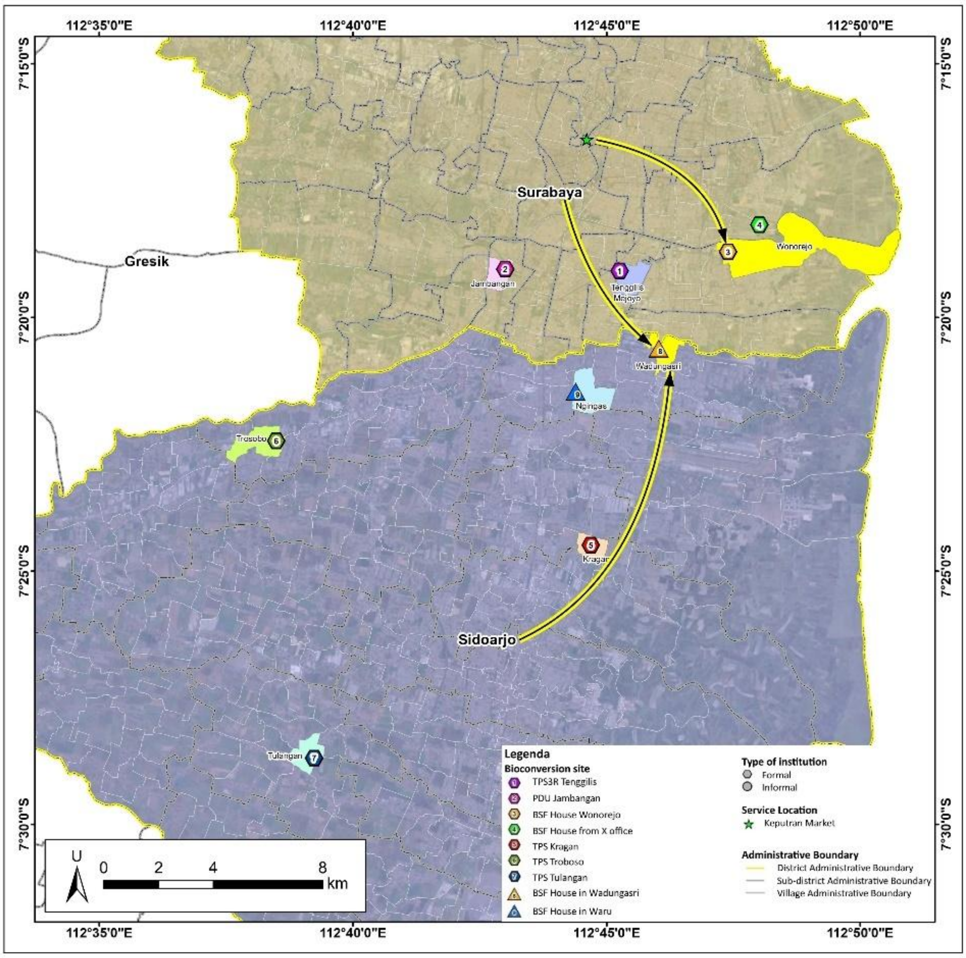

Figure 5. Flow of waste sources treated at the bioconversion facility

3.4. Potential of Waste as BSF Substrate

The above mapping results were used to estimate the quantity of waste that can serve as a substrate source for BSF bioconversion (Table 5). Two primary types of waste are considered: fruit and vegetable waste from markets and bread scraps from bakeries. The selection of fruit and vegetable types used in this estimation is based on research conducted by Fitriana et al. (2025).

Table 5. Estimation of potential vegetable and fruit substrates for BSF bioconversion

City/Regency	Number of markets	Waste generation (ton/day)	Fruit-vegetable waste (ton/day)	Selected waste (ton/day)
Surabaya	67*	52.49	38.77	18.25
Sidoarjo	19**	14.88	10.93	5.15
Total	86	67.37	49.70	23.40

*Central Bureau of Statistics Surabaya (2024); ** Central Bureau of Statistics Sidoarjo (2024)

According to Mujaddid (2021), the average market waste generation in Surabaya City's eastern region was 783.39 kg per day. Research indicated that the composition of fruit and vegetable waste in Surabaya market waste was 73.86% (Mujaddid, 2021), while in Sidoarjo Regency was 73.46% (Triyanto, 2023). Based on this study's mapping results, the composition of selected vegetable and fruit waste was 47.09%. However, it was not possible to estimate the quantity of rejected bread due to the lack of available data on the number of bakeries in both Surabaya City and Sidoarjo Regency.

According to Fitriana et al. (2025), the optimum substrate composition was a 4:3:3 ratio of creamer, vegetables-fruit waste, and bread, with final products consisting of 19.72% fresh larvae and 23.81% frass. In this study, since not all vegetable-fruit waste can be processed entirely; the quantity must be adjusted using the recovery factor (RF). This calculation is essential for determining both the proportion of waste that can be used and that cannot be reused. The RF value for fruit and vegetable waste is similar to that of compostable food waste, which is 48.21% (Pradiptiyas, 2018). The bioconversion potential in Surabaya City and Sidoarjo Regency is presented in in Table 6.

Table 6 The potential for bioconversion substrates in Surabaya City and Sidoarjo Regency

City/Regency	Fruit-vegetable waste (ton a day)			Bread (ton a day)		Creamer (ton a day)		Total of substrate (ton a day)*
	Wet weight		Dry weight	Wet weight	Dry weight	Wet weight	Dry weight	
	Total	Can be processed						
Surabaya	18.25	8.80	1.47	1.78	1.47	2.02	1.96	12.60
Sidoarjo	5.15	2.48	0.42	0.50	0.42	0.57	0.55	3.55
Total	23.40	11.28	1.89	2.29	1.89	2.59	2.52	16.16

*Wet weight

Table 7 below illustrates the bioconversion substrate potential of rejected bread obtained from the surveyed bakeries for BSFL cultivation.

Table 7 The substrate potential if all rejected bread from surveyed bakeries is used

Fruit-vegetable waste (kg a day)			Bread (kg a day)		Creamer (kg a day)		Total of substrate (kg a day)*
Wet weight		Dry weight	Wet weight	Dry weight	Wet weight	Dry weight	
Total	Can be processed						
386.76	186.46	31.18	37.80	31.18	42.78	41.57	267.04

* Wet weight

For every 37.8 kg/day of discarded bread, an additional 186.46 kg/day of selected fruit-vegetable waste and 42.78 kg/day of rejected creamer are required as supplementary substrates. Over a 14-day cultivation cycle, this results in a total substrate input of 3.74 metric tons.

3.5. Potential Products of BSFL Bioconversion

The potential yields of larvae and frass generated are detailed in Table 8, based on a single rearing cycle lasting 14 days. After 14 days of feeding, 1 ton of substrate from Surabaya City and Sidoarjo Regency produced 0.2 tons of wet larvae (equivalent to 0.07 tons of dry larvae) and 0.24 tons of wet frass. On the other hand, to produce one ton of wet larvae, approximately 5.07 tons of substrate are required over a 14-day period. The product potential from processing all rejected bread are 0.74 tons of fresh larvae biomass and 0.89 tons of fresh frass as byproduct.

Table 8 Potential larvae produced in Surabaya City and Sidoarjo Regency

City/Regency	Substrate (ton per 14 days)	Larvae (ton)		Frass (ton)	
		Wet weight	Dry weight	Wet weight	Dry weight
Surabaya	176.45	34.79	12.50	42.00	16.16
Sidoarjo	49.77	9.81	3.53	11.85	4.56
Total	226.22	44.61	16.03	53.85	20.72

3.6. The Economic Potential of BSFL Bioconversion Products

Market data collected from black soldier fly (BSF) bioconversion facilities indicate that fresh larvae are currently valued at IDR 10,000 per kilogram. In the time of the research conducted, 1 USD is equal to IDR 16,656. Previous studies (Camila, 2022) have reported frass prices at IDR 3,000 per kilogram, while processed dried larvae command a premium market value, ranging from IDR 85,000 per kilogram depending on product quality. A comprehensive economic analysis, including these price parameters, is presented in Table 9.

Table 9. The economic potential of bioconversion products

Type of products	Price (Rp/kg)	Per cycle		Per ton substrate	
		Quantity (kg)	Income potential (IDR)	Quantity (kg)	Income potential (IDR)
Fresh larvae	10,000	44,608	446,076,876	197	1,971,900
Dry larvae	85,000	16,025	1,362,140,161	71	6,021,394
Fresh frass	32,000	53,853	161,557,704	238	714,172

Market analysis reveals a significant price differential between processed and unprocessed larval products, with dried larvae commanding premium market value compared to fresh specimens. The dehydration process, conducted at 50°C for 7 hours (Natsir et al., 2020), adds substantial value to the final product. Economic projections demonstrate that processing one metric ton of substrate yields IDR 2,686,072 for fresh larvae sales versus IDR 6,735,566 for dried larvae. Scaling to full production capacity, potential revenues reach IDR 607,534,580 per cycle for fresh larvae and IDR 1,523,697,865 for dried larvae, illustrating the considerable economic advantage of value-added processing.

The economic analysis followed methodologies established by Camila (2022) for calculating investment and operational-maintenance (O&M) costs. This economic analysis evaluates two distinct operational scenarios for BSFL and frass productions. Scenario 1 models fresh larvae commercialization, excluding: (1) oven procurement costs, (2) substrate collection transportation expenses, and (3) palletization equipment investments. Operational expenditures in this scenario incorporate only partial electricity consumption (estimated at 33% of total drying-related energy costs based on Camila (2022)). Scenario 2 examines dried larvae production, including oven acquisition costs while similarly excluding substrate transportation and palletization equipment. This configuration accounts for full electricity expenditures as documented Camila (2022). For BSF-based waste management systems, the initial investment required IDR 175,960,000 with annual O&M costs of IDR 165,578,137/year, including substrate transportation expenses, pelletizer machine, and oven. At the pilot scale (1.2-2.5 tons processed), this translated to per-ton costs for investment and O&M cost per cycle. Scaled to full operational capacity as detailed in Table 6 (16.16 tons/day; 226.216 tons/14-day cycle), the projected total costs can be seen on Table 10.

Table 10 The investment, O&M cost, dan Profit potential

Scenario	Investment (IDR)	O&M Cost (IDR)	Income potential (IDR)	Profit (IDR)
Selling fresh larvae	10,633,410,718	549,545,681	607,634,580	58,088,900
Selling dried larvae	15,646,863,333	554,091,330	1,523,697,865	969,606,535

The economic analysis revealed substantial differences in profitability based on product form, with fresh larvae sales generating a profit of IDR 58,088,900, whereas dried larvae commercialization yielded significantly higher returns of IDR 969,606,535. This 16.7-fold increase in profitability underscores the considerable economic advantage of value-added processing in black soldier fly production systems.

4. Conclusions

The bioconversion of organic waste in and around Surabaya holds significant potential for the production of larvae and frass. Fruit and vegetable waste in the market is dominated by year-round fruits (53.9%) and other categories of vegetables (64.1%) and dark green vegetables (26.5%). The average amount of rejected bread was 2.6-2.7 kg of bread. Rejected products from the industry include creamer, condensed milk, and fresh milk. With the potential for organic waste that has been surveyed, the daily processing capacity of the substrate is 16.16 tons, yielding 44.61 tons of fresh larvae and 53.85 tons of frass with a potential profit of IDR 58,088,900 (if sold as fresh larvae) and IDR 969,606,535 (if sold as dried larvae). Bakeries inside malls have great potential to produce rejected bread. However, this study encountered licensing constraints, so the survey of bread by-products was only conducted at facilities located outside the mall. Further research should investigate the waste stream from bakeries inside the mall to provide more comprehensive data. Additionally, this study could only calculate the potential for bioconversion substrates from the mapping results and the potential products along with economic analysis, but there was no analysis of product quality. Therefore, the researchers hope that further research will be conducted to discuss product quality and its intended use in more detail.

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