Enhancing Black Soldier Fly (BSF) Supply Chains to Reduce Production Costs For Smallholder Farmers in Communities, Thailand

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Abstract: - This research introduces a community-based supply chain management and commercial utilization model for Black Soldier Fly (BSF) larvae. This model aims to address the significant challenge of high production costs within the Thai agricultural sector, particularly concerning animal feed and organic fertilizer, which pose major obstacles for small-scale farmers. The model is developed based on value chain theory and circular economy principles, emphasizing the coordinated integration of all value-added activities, from raw material sourcing and production to distribution and waste management. The proposed model comprises five main components. (1) Organic waste sourcing and separation: Collect organic waste from households and communities to be food for BSF larvae, with the participation of local administrative organizations and waste sources in the community. (2) Feed preparation: prepare organic waste suitable for BSF larvae, with the participation of community enterprises, farmers, and supporting agencies. (3) BSF larvae farming: Breed BSF larvae in a controlled environment greenhouse, with farmers and community enterprises as the breeders. (4) By-product processing: process adult BSF larvae into protein for animal feed, organic fertilizer (frass), and insect oil, with community enterprises playing an important role in processing and packaging. (5) Distribution and value creation: link products to local markets through community enterprises and partners to generate income that is reinvested in the project.

Key-Words: - Agricultural Supply Chain, Bio-Circular-Green Economy, Black Soldier Fly (BSF), By- product Utilization, Organic waste, Production Cost, Smallholder Farmers.

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1 Introduction

The production costs of the agricultural sector, especially in the animal feed and organic fertilizer categories, tend to increase continuously. Animal feed accounts for more than 60–70% of total animal husbandry costs. [1] in addition, the prices of key raw materials, such as animal feed, corn, and soybean meal, have increased by an average of 25–30% during 2022–2023 due to the economic crisis and logistics uncertainty [2], causing smallholder farmers to bear the burden of increased costs and risk their long-term economic security.

Research as [3] and [4] indicates that smallholder farmers in developing countries often face fluctuations in input prices and lack access to transparent and efficient supply chains. The cost structure of the animal feed industry in Thailand indicates that more than 84% the cost is raw materials, with the main raw materials being animal feed corn (33%) and soybean meal (23%) [5], which are still reliant on imports. Reducing dependence on these raw materials is therefore an important issue for sustainable development in the agricultural sector. At the same time, Thailand has a large amount of organic waste at the community level that has not been effectively managed. The Black Soldier Fly (BSF) has been proposed as an alternative to convert organic waste into animal feed protein, organic fertilizer, and valuable oil, but there is still a lack of a community-level supply chain system that farmers can access and manage sustainably. Supply chain management and strategic business design related to agricultural development can apply the supply chain management (SCM) theory that emphasizes the coordination and management of resources from the beginning to the end [6] and use the circular economy concept that aims to reduce waste and increase the reuse of resources, with integration from raw material procurement, production, distribution to waste management [7] to be integrated with BSF management.

For the disposal of organic waste with black soldier larvae, it is the use of organic waste to produce new uses (Recycle), an alternative protein for production, or to be used as animal feed and fertilizer to reduce disposal (Disposal) by burning or burying. Disposing of organic waste with black soldier larvae can reduce greenhouse gases 47 times more than the method of making compost. [8] currently, there are research studies that mention the potential of BSF in terms of biology and environment, such as [7], [9], and some case studies in Thailand, such as the BetterFly project, [10]. However, there is still no design of a business supply chain system that focuses on the goal of truly "reducing costs" for farmers. This research aims to propose a model to help farmers reduce costs by efficiently using local resources, creating shared value, and flexibility by applying BSF, a local bio-raw material, to reduce dependence on uncertain trade systems, and also help improve the management capabilities of smallholder farmers in the long term.

2 Theoretical Frameworks

The cost of production of agriculture, especially in terms of animal feed and organic fertilizer, is a major obstacle for smallholder farmers in Thailand. This research aims to propose a model for supply chain management and commercial utilization of Black Soldier Fly (BSF) by-products at the community level. This model is based on the Value Chain Theory, which emphasizes the coordination of all value-adding activities in bringing a product or service from the beginning to the various stages of production and delivery to the consumer, including sourcing, production, transportation, sales, and final customer. It also emphasizes the involvement of key partners and communities, [6], [11]. Another concept, the circular economy, which is part of the BCG Model, was first proposed by Kenneth Boulding in 1966. It is closely linked to the concept of sustainability, focusing on renewable energy production, terrestrial and aquatic biological resources, and converting resources and waste into value-added products such as food, animal feed, bio-products, and bioenergy. It promotes the use of circular resources, integrating everything from raw material sourcing, production, distribution, to waste management. The motivation behind the circular economy is therefore the conservation of natural resources. [9], [12] therefore, the concept of the circular economy must rely on innovation and technology.

3 Materials and Methods

The research was conducted in 4 regions of Thailand: the north (Chiang Mai province), the northeast (Khon Kaen province), the east (Chon Buri province), and the south (Songkhla province). The criteria for selecting the study areas were: being the provinces with the highest volume of solid waste in the top 10 of the country, and being strategically located at the center of the region. Chonburi province has the highest amount of waste in the country, approximately 3,107 tons per day. Chiang Mai province has the 4th highest amount of waste, at 1,445 tons per day. Khon Kaen province has the 7th highest amount of waste, at 1,348 tons per day. Songkhla province has the 8th highest amount of waste, at 1,207 tons per day.

The research instruments were a data recording form and an observation form. Descriptive statistics were used to analyze the data to compare the data recorded at each time period and the content analysis from the observation data collection. The analysis results were used to design and improve the BSF supply chain model. Research period: start date: May 1, 2024, project end date: May 31, 2025.

We quantify cost impacts of integrating Black Soldier Fly (BSF) products through a controlled pre–post field experiment, comparing matched farm households using conventional practices (baseline) with households adopting BSF larvae for layer feed, frass for fertilizer, and BSF exuviae/parts for plant biostimulant extraction (treatment) over 12 weeks for poultry and one crop cycle for vegetables. Operational protocols will follow documented BSF rearing guidance: maintain 25–30 °C and 75–85% relative humidity, feed at ~1:1 (larval biomass: biowaste, wet basis), and keep feed layers <10 cm to avoid overheating and odor.

4 Results and Discussion

The study developed and proposed a comprehensive BSF-based organic waste value chain model specifically designed for application in smallholder agricultural communities. The model consists of five core components that work synergistically to transform low-value organic waste into economically viable agricultural inputs.

The first stage, waste sourcing and segregation, involves the collection of household food scraps and agro-industrial residues from local communities, sorted to ensure suitability for larvae feed. Participants in the process are important sources of waste in the community, such as markets, schools, temples, condominiums, offices, department stores, hotels, especially households in the community, local administrative organizations play a key role in this process by introducing various measures and guidelines to reduce community waste, promote waste separation from the beginning to dispose of organic waste at the greenhouse. Receiving organic waste to be used as BSF food from all 4 locations throughout the project period: Chonburi province, total organic waste weight 17.19 tons, imported 61 times; Songkhla province, total 58.34 tons, imported 91 times; Khon Kaen province, total 40.12 tons, imported 82 times; Chiang Mai province, total 47.57 tons, imported 82 times. As shown in Table 1, all study areas achieved substantial reductions in organic waste during the project period compared with the baseline before project initiation.

Table 1. Comparison of the amount of organic waste before and after the project

province	amount of organic waste before initiation (kg/day)	amount of organic waste in the project period (kg/day)	Percentiles (%)
Khon Kaen	5,000.00	415.96	91.68
Chiang Mai	2,000.00	406.98	79.65
Chon Buri	1,000.00	181.63	81.84
Songkhla	100,000.00	407.58	99.59
Total	108,000.00	1,412.15	352.76

Source: created by the authors

All areas achieved a reduction of more than 70% in organic waste, with the project averaging 97.6% across the entire project. The project achieved the greatest reduction, reducing 99.59% of organic waste in Songkhla Province. Even smaller project areas, such as Chiang Mai and Chonburi, achieved waste reductions of 79.65% and 81.84%, respectively.

The second stage, substrate preparation, includes chopping, moisture adjustment, and microbial conditioning to enhance larval digestion and conversion efficiency. The participants are community enterprises, farmers, local administrative organizations, agricultural extension agencies, local universities, technical consultancies, training workshops, and greenhouse equipment distributors. BSF carries out the activities mentioned above, as well as the process of designing and developing the greenhouse and preparing various materials and equipment within the greenhouse for breeding and disposing of organic waste. The greenhouse is divided into 6 zones as follows: (1) food waste receiving and food grinding zone, (2) larvae nursery zone, (3) breeding zone, (4) insect egg-laying hangar zone, (5) larvae rearing zone, (6) cement plant zone. This research developed an appropriate environment for raising them, with a temperature between 25-30 degrees Celsius and a humidity of 75-85%, allowing BSF to grow best and decompose 90% of the organic waste received into the barn within 14 days. Humidity control is essential because excessive humidity can cause unpleasant odors.

In the third stage, BSF rearing, larvae are cultivated in environmentally controlled units that regulate temperature, humidity, and light, ensuring consistent growth and yield. The main participants in raising BSF are farmers and community enterprises. The details of the steps are presented in Figure 2 because the life cycle of the black soldier larvae is to eat 24 hours a day and eat all kinds of food in large quantities. In other words, the black soldier larvae will eat twice the amount of their body weight every day. To create a clearer picture, the food intake of larvae is like a person who weighs 60 kilograms but has to eat 120 kilograms of food per day, and the growth of larvae can expand up to 1,000 times. [7] the fourth stage focuses on by-product processing, where mature larvae are harvested and processed into protein-rich animal feed, frass organic fertilizer, and insect oil. These outputs are then packaged, quality-checked, and stored. The main participants are community enterprises, which are responsible for the product processing, packaging, and distribution channels within the community, local agricultural stores, online agricultural markets, and local administrative organizations responsible for product distribution and sales. Customer Segments are smallholder farmers, community enterprise groups, agricultural schools, animal farms, and bioproduct producers. Activities in this stage are packaging, quality inspection, and storing the product for sale. Since BSF has a high protein content of 40-60% and fat of 15 to 35% by weight, when BSF is dried, it is popularly processed into animal feed by processing it into pellets for feeding chickens, ducks, frogs, and fish. From experiments, using it to feed chickens can reduce feed costs by up to 60%. The pupae of BSF and dead adults are used as planting materials mixed with soil because they are rich in calcium, which helps strengthen plants.

The fifth stage, distribution and value capture, connects products to local markets through community enterprises, cooperatives, or municipal partnerships. Revenue from product sales is reinvested into operations, training, and equipment maintenance, ensuring long-term viability. As shown in Figure 1.

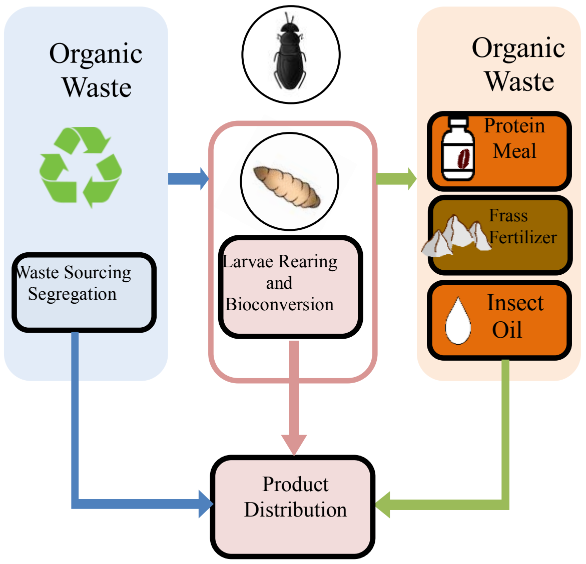

Fig. 1: BSF-Driven Organic Waste Value Chain in Agriculture
Source: created by the authors

Control system design guidelines for the project, a prototype greenhouse was developed that controlled key environmental factors, including temperature, humidity, light, carbon content, and air circulation, using an IoT system to collect real-time data. This approach is based on the work of [13], which showed that precise environmental control can significantly improve the efficiency of BSF farming. This research estimated that each greenhouse supports BSF farming from approximately 400 kilograms of organic waste per day. We have designed a waste disposal kit using biotechnology in a controlled environment. Patent No. 2033000787 BSF raising process (1) BSF eggs, beginning of life cycle: larval eggs are oval, 1 mm long, milky white, and start to turn creamy white until becoming light yellow. Stage 1-2 days, emerge from egg; 3-4 days, begin to see pods as larvae. (2) BSF larvae have a plump, oval, flat body, creamy white, 3-27 mm long. Days 5-20, molt 6 times, weight approximately 0.1-0.3 grams. Useful as animal feed in the following forms: sifting only the larvae to be animal feed, using both the larvae and manure trays, incubating the larvae to store as animal feed for a long time, and some larvae can be used to make organic fertilizer. (3) BSF pupa and pupal case, body starts to change color from cream to dark brown and black, skin is hard and dry, likes dry and dark places, body is bent. Days 21-30, the pupal case has high chitosan, which can be used in industry or as an alternative product. (4) Adult/flying carcass, will discard the case, black case is hard, dry, crisp, lightweight. Pupa inside becomes adult and flies outside, body length is 16 mm, black color, female/male are different at the bottom, lay the pupa on a dry surface for 4 days as shown in Figure 2.

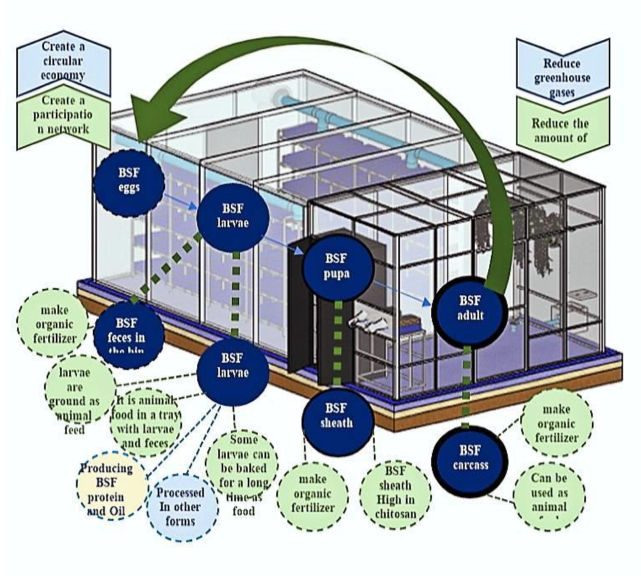

Fig. 2: Valorization of Organic Waste through BSF
Source: created by the authors

The size and completeness of larvae with biotechnology waste management kits in controlled environments found that: The size of larvae and the number of eggs are different from the conventional rearing. The larvae are larger than normal, and more BSF eggs are laid than in the conventional rearing. In other words, the larvae have a thick, creamy white body with a body length of 3-27 millimeters and molt 6 times. The rearing with biotechnology waste management kits in controlled environments resulted in larvae weighing 0.1-0.3 grams when approaching the pupal stage. They will start moving out of wet food to areas with dry and dark food to begin the pupal stage. During this time, some of the larvae can be sifted to be animal feed. Size of the pupa: body length 27 - 30 millimeters, and curved when the larvae begin to enter the pupa stage or the black body stage, they will not eat food, so there is no need for food in the tray. Later, the larvae's skin will start to become darker and darker until it is black. The skin of the larvae will start to dry and harden. The tray left over from dividing it up to feed animals is brought to the hangar to prepare to enter the adult stage. Size of BSF adults: the body can be up to 16 millimeters long. When they start flying, they start mating between males and females, which are different at the tip of the body. The adult female is larger, and the tip of the body (butt) is more pointed than the male's, to be used for laying eggs. This controlled environment will have both real and fake trees as flying grounds for the adults. The controlled conditions will prevent disturbances during the important mating period.

Egg laying of adults bred with the biotechnology waste management unit in a controlled environment, it was found that the egg laying method in a prepared area using horizontal pairs of sticks, leaving a small space between the two pieces of sticks, so that the female can poke her buttocks to lay eggs. Laying eggs in the hangar in a controlled environment will result in a larger number of eggs than normal because flying insects are not disturbed. The area is surrounded by mosquito nets. Real and fake trees are placed to simulate nature and are in a more suitable condition.

In conclusion, the life cycle of Black Soldier Fly or BSF Life Cycle, which is cultivated with a biotechnology waste management kit in a controlled environment, is shorter than the traditional farming model. The shortest period is around 34 days, and the longest is around 45 days or more, depending on the amount of food, the packing of larvae in trays that are not too dense, and the controlled conditions at an appropriate temperature. The difference that affects the growth of larvae can be measured from the growth period in each stage of the BSF life cycle, the size and weight of the BSF larvae, and the number of BSF eggs collected. Products from BSF can produce protein and fat from larvae or pupae, which can be processed into other products such as animal feed supplements or used in cosmetics, medicines, and as organic fertilizers.

Adult larvae can be used to feed fish, poultry, and pigs. Fertilizers resulting from the disposal of organic waste are feces and remains of larvae that are used in agricultural plots, rice cultivation, and vegetable plots. Table 2 (Appendix) summarizes the amount of organic waste processed and the quantity of BSF-derived products obtained in each of the four study areas, including larvae used as animal feed and adult remains used as fertilizer. In this research, BSF was able to dispose of 200-250 kg of organic waste per day, where 100 kg of organic waste will yield approximately 60 kg of black soldier larvae for animal feed. This is consistent with the work of [2], who proposed that BSF can effectively replace fishmeal in animal feed, which helps farmers reduce their feed purchasing costs by 300 baht per day. (Calculated from the cost of catfish food at 25 baht per kilogram, using a meat exchange rate of 1:1 and a meat exchange rate of black soldier larvae obtained from the disposal of organic waste at a rate of 1:5) and obtaining approximately 30 kilograms of fertilizer to be used in agricultural plots, rice cultivation, and vegetable plots. Just 1 kilogram of black soldier larvae eggs, when cultivated until fully grown, has the potential to eliminate 13 tons of organic waste throughout the BSF's life. Although the research results showed the ability to dispose of 200 -250 kg of organic waste per day and the target of producing no less than 100 kg of BSF larvae per day to dispose of no less than 400 kg of organic waste per day, the use of BSF still significantly reduces the cost of disposing of organic waste.

The results were evaluated using a difference in pre-post comparison experiment, supported by paired t-tests and mixed-effects models (random effects on farms). Table 3 (Appendix) presents the comparative agricultural costs before and after BSF utilization across major farm inputs. The agricultural costs and savings from BSF implementation were analyzed as follows:

However, cost outcomes are highly dependent on local prices (fishmeal/soybean price vs. larvae), logistics for drying or feeding fresh larvae, and plant nutrient requirements.

5 Conclusion

This research is an extension of previous research on BSF, such as the work of [7] and [9], which focused on the transformation of organic waste with BSF in a biological and environmental sense, but did not focus on business and supply chain aspects. Meanwhile, [11] studied in the Vietnamese context and found that although BSF can manage waste well, it still cannot control the quality of products, and there is no complete market system for by-products. In addition, the research of BetterFly SWITCH-Asia [14] focuses on promoting BSF farming at the community level in a technical sense, but there is still no supply chain model covering upstream-midstream-downstream systems with a clear business model for farmers. The results of this research indicate that this model has, [10]. They found that black soldier flies are an important alternative protein source for small-scale or medium-scale farmers and can be used as a cost-effective ingredient for fish feed. High potential to reduce production costs for smallholder farmers, add value to organic waste, and promote a circular economy at the community level, consistent with the study of [10].

The steps for implementing organic waste disposal using black soldier can be summarized as follows:

1. Promoting community waste management at the source, with local government agencies participating in reducing community waste generation, promoting waste separation at the source, and reducing food and organic waste destined for landfills.
2. Designing and developing a facility for organic waste disposal using biotechnology in controlled environments using black soldier.
3. Coordinating the collection and transportation of organic waste to a prototype facility.
4. Building a network of local farmers who want to reduce animal feed costs with black soldier.
5. Selling black soldier larvae and adult remains to the animal feed and fertilizer markets.

The research is conducted in the target areas to develop a prototype of an organic waste disposal system using Black Soldier Fly (BSF) with a focus on application at the household, community, and business levels in Thailand.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

APPENDIX

Table 2. Summary of the results of converting organic waste into black soldier beetle products throughout the project period in 4 areas

province	**The amount of organic waste received for decomposition and BSF larvae rearing during the project period (kg)**	**The amount of BSF larvae that can be produced from decomposing organic waste (Kg/Ppercentile)**	**Larvae used as animal feed (Kg/Percentile)**	**The remains of adults after mating are used as fertilizer or organic compost. (Kg/Percentile)**
Khon Kaen	40,129.00	6,869.00 (17.12%)	6,779.00 (16.89%)	66.30 (0.16%)
Chiang Mai	47,576.00	7,000.35 (14.71%)	6,892.35 (14.49%)	88.50 (0.18%)
Chon Buri	17,191.00	2,950.10 (17.16%)	2,852.60 (16.59%)	70.10 (0.41%)
Songkhla	58,348.00	12,900.25 (22.11%)	12,769.25 (21.88%)	103.50 (0.18%)
Total	163,244.00	29,719.70 (18.20%)	29,293.20 (17.94%)	328.40 (0.20%)

Source: Created by the authors

Table 3. Comparative Table: Agricultural Costs Before and After BSF Utilization

Agricultural Input	**Conventional Practice (Before BSF)**	**With BSF Integration**	**Estimated Savings**
Feed for laying hens.	Fishmeal/soybean meal at ~14–16 THB/kg; accounts for 60–70% of total egg production costs	BSF larvae (fresh/dried) mixed with rice bran, ~6–8 THB/kg	30–60% reduction in feed costs; ~1,500–2,000 THB/month per 100 hens
Crop fertilizer	Chemical fertilizer ~12,000–15,000 THB/rai/year	BSF frass as organic fertilizer ~2,000–3,000 THB/rai/year	70–80% reduction; ~10,000 THB/rai/year
Biofertilizer solution	Purchased products at 50–100 THB/litter; 1,000–3,000 THB/rai/year	Fermented BSF pupal cases and wings; 10–15 THB/litter	800–2,500 THB/rai/year

Source: Created by the authors