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Research Article
Reproductive Potential and Population Parameters of *Hermetia illucens* (Diptera: Stratiomyidae) Reared on Tofu Dreg

Ucu Julita, Lulu Lusianti Fitri, Ramadhani Eka Putra and Agus Dana Permana

School of Life Sciences and Technology, Institut Teknologi Bandung, Jalan Ganesha No. 10, Bandung 40132, Indonesia

Abstract
Background and Objectives: Black Soldier Fly (BSF), *Hermetia illucens* (Diptera: Stratiomyidae) has long been studied primarily in terms of their important role in organic waste management. This species has a special ability to digest a variety of organic matter, from vegetable waste, food waste, decaying animal tissues to livestock manure and then convert to nutritional biomass for animal feed. The different types of feed during the larval period will affect the life history of black soldier fly. This study was aimed to determine the development, survival, population parameters and reproductive potential of the BSF reared on tofu dreg by the age-stage, two-sex life table analysis. **Materials and Methods:** The treatments of immature stages were constructed under laboratory conditions and the adult stage were reared at a semi-outdoors screenhouse with full sunlight. **Results:** The intrinsic rates of increase (r), finite rate of increase (λ), net reproduction rate (R_0) and mean generation time (T) were 0.0713 per day, 1.0739 per day, 23.95 offspring and 43.705 days, respectively. The result indicated that the maximum reproductive value of females occurred at 42 days. The overall development time from egg to adult stage of the BSF was 52.2±1.6 days. **Conclusion:** The BSF can perform optimal development, survival rate and reproductive potential when reared on tofu dreg.

Key words: *Hermetia illucens*, life table, intrinsic rate of increase, finite rate of increase, reproductive value, survival rate, tofu dreg

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Corresponding Author: Agus Dana Permana, School of Life Sciences and Technology, Institut Teknologi Bandung, Jalan Ganesha No. 10, Bandung 40132, Indonesia

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Tofu is one of the most popular side dishes consumed in Indonesia. Based on the data from the Ministry of Agriculture in 2019, Indonesian tofu consumption per capita reached 7,28 kg/person/year. This number is higher than per capita consumption of beef, fish and chicken. The solid waste generated from the tofu production process is one of the environmental problems caused by tofu industries. The tofu industries generally produce solid waste for about 40% of the total capacity of 100 kg soybean production and the tofu industries in Indonesia can spend about 2.56 million tons of soybeans every year for the tofu making processes[1]. The solid wastes from the tofu industries contain a lot of organic substances, if not handled well or being stored for too long will release a bad odour and cause a negative impact to the environment[2]. Tofu waste management with eco-friendly processing and high benefit is needed.

The BSF larvae are effective bio-recyclers and are highly demanded organic waste management. The BSF is a non-pest tropical insect and one of the best insects for bioconversion[3] that is useful for managing large concentrations of animal manure and other biosolids[4]. The BSF larvae have an extremely voracious appetite and are capable to consume a wide range of organic waste, including food waste, household waste[5], fruits and vegetable waste[6,7], animal manures[8-10] and even some indigestible food, such as crop straw[11,12], coffee pulp[13], maize straw[14] and palm kernel meal[15]. The BSF offer a lot of benefits when recycling the nutrient from organic waste into nutritious biomass. Some of them are waste biomass reduction, odour reduction, housefly control, emitting relatively fewer pollutants, adding value to the waste, producing highly protein feedstock and providing sustainable bio-energy resource[16-19]. The BSF prepupa provide additional nutrition for animal feedstuff, such as fish[20], chicken[21,22] and pigs[23].

Tomberlin *et al.*[24] reported that the development and life-history traits of BSF are highly dependent on the rearing substrates used for larvae. The larval stage happens to be the most crucial stage of BSF related to organic waste management, as this is the stage at which feeding activity occurred and is converted to other desirable biomass products[25]. The life history of adult BSF depends on the quantity and quality of food supply for the larvae because there is no feeding activity when BSF is in the adult stage[26]. The life-table analysis provides comprehensive and summarizes the survivorship and reproductive potential of insect populations[27]. According to Huang and Chi[28], the age-stage, two-sex life table generates an improvement over the previous life table because it illustrates stage differentiation and considers the male individual. Furthermore, age-stage, two-sex life tables can precisely reveal the actual life history of the insect species and describe in detail of development, survival, fecundity and life expectancy of a population as a means of projecting the growth of populations[29]. Therefore, the present study aimed to assess the development, survival, fecundity and reproductive potential of the black soldier fly reared on tofu dregs as growing substrate with a two-sex life table analysis. This data will be useful for applying BSF as a bio-converter agent of tofu waste which is economically valuable and concurrently reduce environmental impact.

MATERIALS AND METHODS

Study sites: This study were conducted for 3 months, from August to October, 2019 in the Laboratory of Animal Physiology and Entomology, Biology Department and in a semi-outdoor screen house in the integrated garden, Faculty of Science and Technology, UIN Sunan Gunung Djati Bandung, West Java Indonesia.

BSF colony rearing and waste material: The colony of BSF were obtained from eggs produced by the adult population reared by the Laboratory of Environmental Toxicology, School of Life Sciences and Technology, Institut Teknologi Bandung, Indonesia. The adult population was originated from larvae fed with tofu dregs and kept in $60\times60\times60$ cm^3 cages with 1.5 mm mesh screen nylon netting. Fresh tofu dreg was collected from home industry tofu at East Bandung, Indonesia.

Life table study: One hundred eggs (<24 hrs old) were selected from the colony reared on tofu dregs, then carefully placed in a plastic cylinder (8 cm diameter by 5 cm high) containing chicken feed mixed with water (60% moisture) to create a medium for eggs hatching. The bottom part is coated with a wet filter paper which was previously dipped in water to maintain the humidity. Larvae hatched from eggs were reared in 100 plastic cups (5 cm diameter by 10 cm high) containing tofu dregs separately per individual with 100 mg/larva/day daily feed rate. The plastic cup was covered by a black sheet to prevent oviposition of other flies and the lid of the cup contained holes to allow air circulation. The larvae were reared until they reach the pupal stage and emerge as adult individuals.

The BSF males and females that emerged on the same day were immediately paired and placed in a 30×30×30 cm adult screen cage (one cage containing one male and one female). The adult rearing cages were equipped with a water source and a wooden ovitrap (length 15 cm, width 5 cm, height 1 cm) placed near on a container filled with rotting organic medium (mixed fruits waste/pineapple, papaya and banana) an attractant for oviposition. All treatments (immature stage) were constructed under laboratory conditions at 25±1°C room temperature and 60-72% relative humidity. The adult rearing cages were placed at semi-outdoors screenhouse with full sunlight. The development time of individuals in all stages both male and female, the daily survival rate and fecundity were observed continued until the last adult individual died.

Data analysis: The data were analyzed using a computer program TWOSEX-MSCHART for the age-stage, two-sex life table analysis in VISUAL BASIC for the Windows system is available at http://140.120.197.173/Ecology/ (National Chung Hsing University, Taichung, Taiwan) and following the procedure described by Chen *et al.*[30]. The population parameters net reproductive rate (R_0), intrinsic rate of increase (r), finite rate of increase (λ) and mean generation time (T) were also calculated. The age-stage life expectancy (e_{xj}) was calculated according to Chi and Su[31]. The means and standard deviations were calculated using the bootstrap method because of the variation among individuals and to fit the normal distribution[32]. The Adult Preoviposition Period (APOP), the duration from adult emergence to first oviposition and Total Preoviposition Period (TPOP), the duration from egg to first oviposition were calculated following the analysis reported by Samayoa *et al.*[33] and Julita *et al.*[6].

RESULTS

The developmental times for each stage of BSF reared on tofu dreg are listed in Table 1. The mean total development time from egg to adult was 52.2±1.6 days, with the longest development time occurring in the larval stage. The Adult Preoviposition Period (APOP) is calculated as the interval between adult emergence and first oviposition. Ignoring the length and variation of immature stages, APOP for BSF reared on tofu dreg is 5.0±2.2 days. The mean TPOP (duration from the birth of a female individual from the egg stage to its first oviposition day) for BSF reared on tofu dreg was 52.6±3.5 days. In this study, only 82% of the eggs successfully hatched into larvae then emerge as 22 females and 25 males after the pupal stage.

Table 1: Stage-specific duration and longevity of BSF reared on tofu dreg

Parameters	Stages	Mean±SE
Developmental time (days)	Egg	3.0±0.0
	Larva	14.8±0.2
	Prepupa	10.2±0.2
	Pupa	10.4±0.2
Adult longevity (days)	Male	14.7±0.2
	Female	13.6±0.4
Total developmental (days)	Egg-adult	52.2±1.6
Adult preoviposition (days)	APOP	5.0±2.2
	TPOP	52.6±3.5
Fecundity (eggs/female)	Female	83.3±39.6

Table 2: Population parameters of BSF reared on tofu dreg estimated by the bootstrap method

Population parameters	Cohort	Bootstrap±SE
r	0.0713	0.0711±0.002
λ	1.0739	1.0737±0.002
R_0	23.95	23.96±0.024
T	43.705	44.491±0.066

The population parameters of BSF in tofu dreg treatments calculated by using the age-stage, two-sex life table are presented in Table 2. The intrinsic rate of increase (r), finite rate of increase (λ), net reproductive rate (R_0) and mean generation time (T) on BSF were 0.0711±0.002/day, 1.0737±0.002/day, 23.96±0.024 offspring and 44.491±0.066 days, respectively. Age-stage-specific survival rate (S_{xj}) of BSF maintained on tofu dregs indicates the probability that newborn offspring will survive to the age x and develop to stage j. The BSF development varies widely among individuals. There are overlaps between developmental stages and within the survival curves (Fig. 1). The first male and female emerged on the same day, on the 34th day and the survival rate of males was higher than females.

The age-specific survival rate (l_x) represents the probability that the newborn offspring will survive to age x (Fig. 2). Age-specific survival rate (l_x) and age-specific fecundity (m_x) were analyzed by considering all individuals of both sexes (male and female). The l_x curve represents the change in survival rates in the cohort by age. Age-specific fecundity curves (m_x) show that the first reproduction of BSF with tofu dregs treatment started on 42 days and maximum age-specific fecundity (m_x) was 31.32 eggs at 46 days.

The lifespan remaining for an individual of BSF reared on tofu dreg at age x and stage j define as the age-stage-specific life expectancy (e_{xj}) (Fig. 3). The age-stage-specific life expectancy (e_{xj}) gives the expected life span an individual of age x and stage j can live after age x. In this study, the life expectancy of a newborn was 33.9 days and the life expectancy of a female was higher than male.

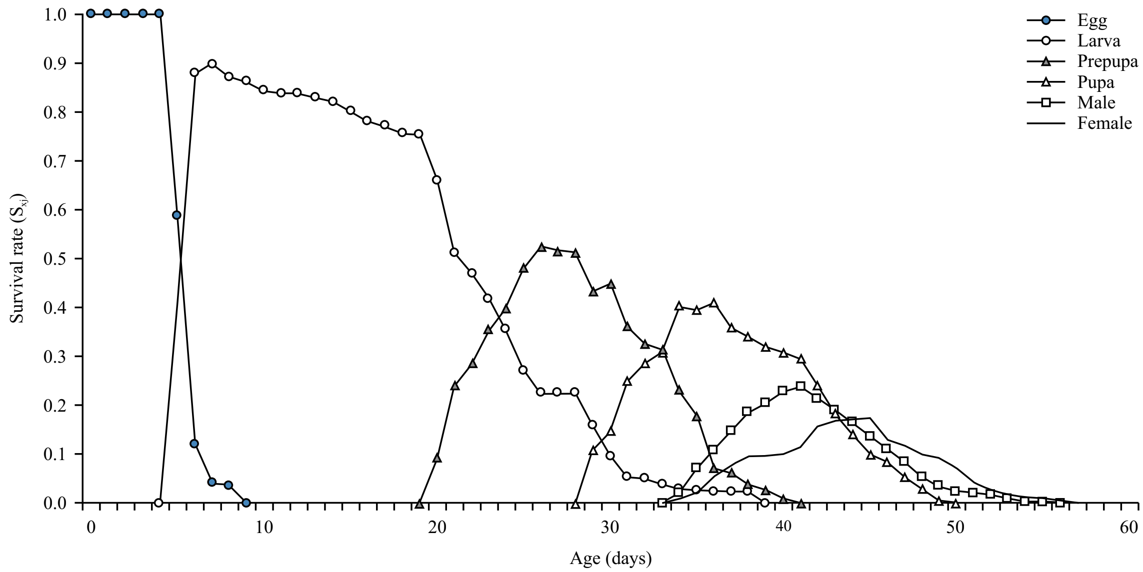

Fig. 1: Age-stage-specific survival rate (S_{xj}) for individuals of age x and stage j of BSF reared on tofu dreg

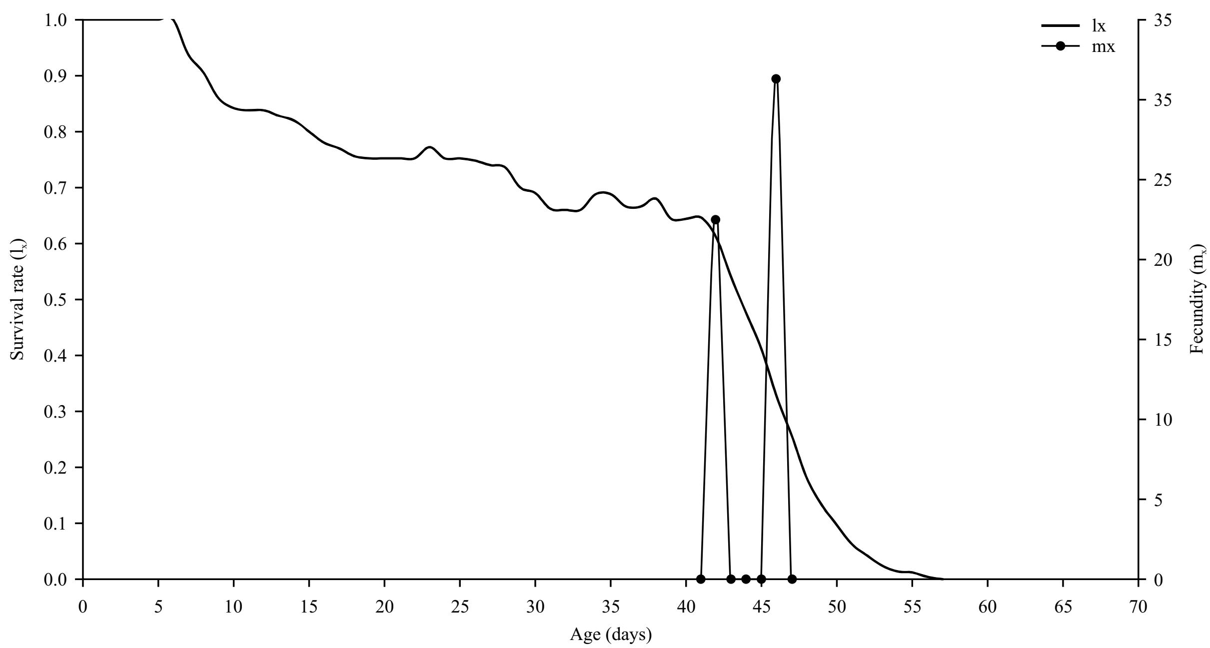

Fig. 2: Age-specific survival rate (l_x) with age-stage fecundity (m_x) of BSF reared on tofu dreg

The contribution of an individual of age x and stage j to the future population is described by the age-stage reproductive value (v_{xj}). The reproductive value of a newborn is exactly equal to the finite rate of increase (1.0739). The reproductive value (v_{xj}) of BSF individuals reared on tofu dreg at age x and stage j is presented in Fig. 4. When a newly emerged female at age 34 days, the reproductive value increases from a value of <30 for an immature stage to 63.41 for a female and peaked to 122.72 at age 42 days.

DISCUSSION

The BSF maintained on tofu dregs, as larval growing substrate, can develop, survive and able to generate offspring in the next generation. According to previous studies, our results confirmed that different feed treatments during the larval period influenced development time, adult longevity, oviposition time, survival rate, fecundity, life expectancy and reproductive value of BSF. Other studies reported mean

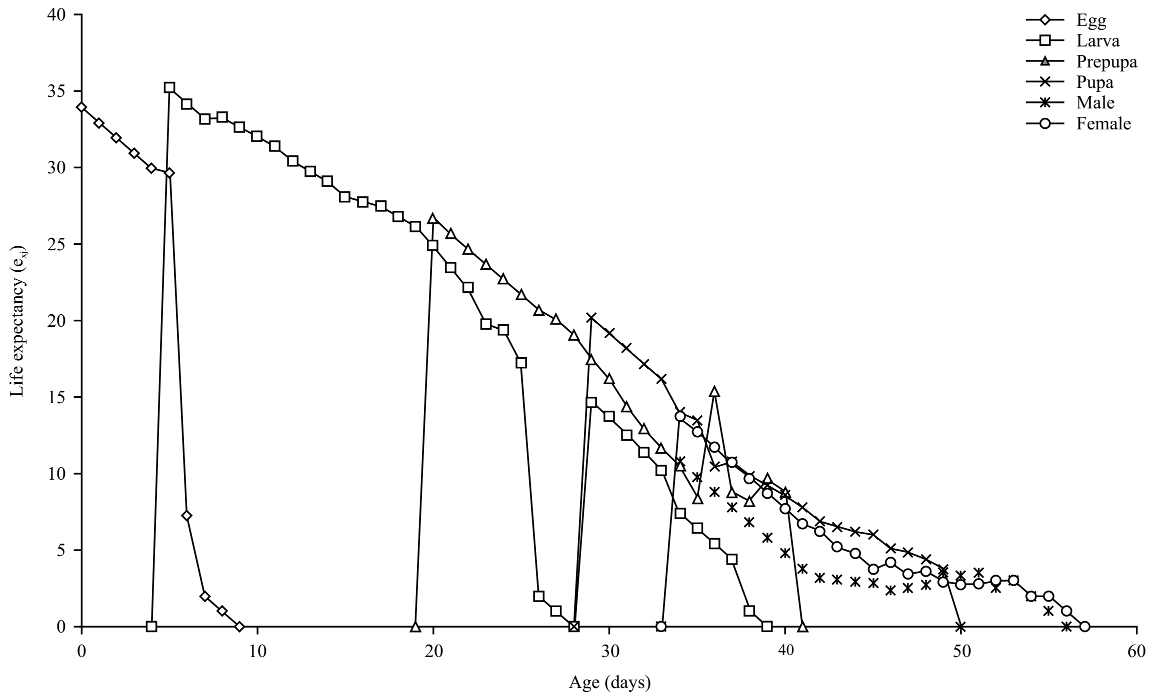

Fig. 3: Age-stage-specific life expectancy (e_{xj}) of BSF on tofu dregs fed treatment

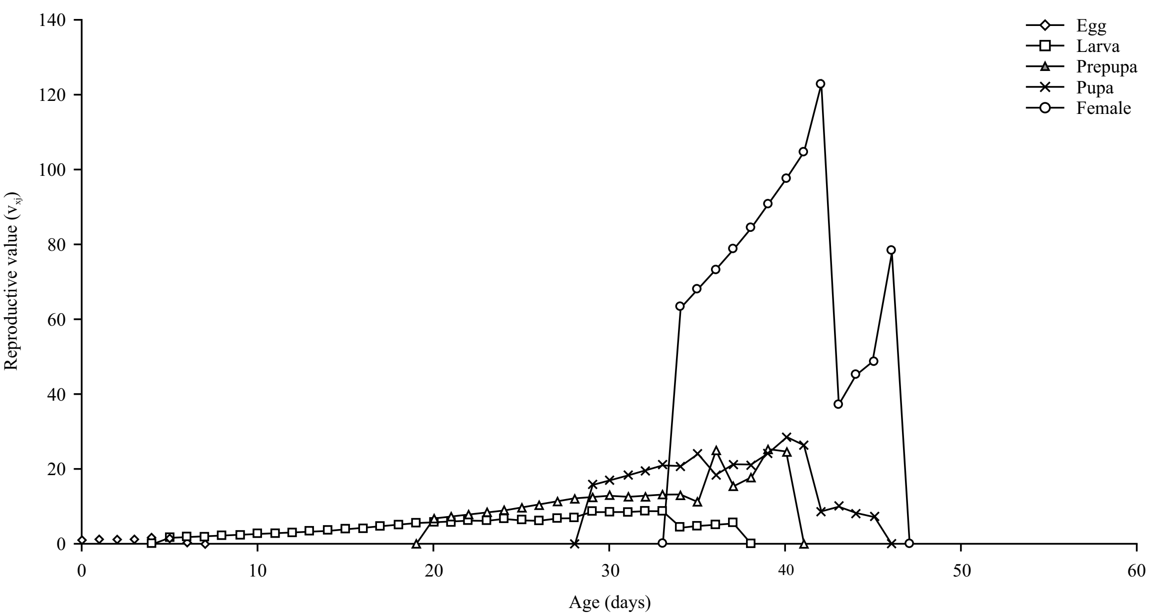

Fig. 4: Age-stage-specific reproductive value (v_{xj}) of BSF reared on tofu dreg

development time of BSF reared in chicken feed, from egg to adult stage was 40-43 days with larval stages 22.5-24.1 days when reared at 27°C[34] and total development time was 47.44 days with a mean larval period of 23.03 days when maintained on artificial feed at 28°C[33]. The total development time of BSF reared on tofu dreg was longer than the total development time of BSF reared on wheat bran and chicken feed[33,34], but much shorter than BSF maintained on yoghurt (77.67 days) and cornflour (42.18 days)[35]. Larval development time in this study was shorter (14.8 days) compared to previous studies which reported the development time of larvae was 28-30 days in dairy manure[18,36], 33 days in meat meal[37], 38-52 days in rice straw[12] and 20-54 days in cassava peel[11]. The larval stage can extend from 2 weeks to 4 months before entering the prepupal stage under unfavourable conditions[38].

The differences in larval development time are due to the quality and nutritional content of various organic wastes as growing substrates. Unlike chicken feed which is designed with all the nutrients for growth, the organic waste contains only certain nutrients that are abundant while other nutrients are lack[21]. Imbalances in feed nutrition can lead to the increase of consumption periods in insect larvae to compensate for nutrient deficiencies, primarily protein and carbohydrates content[39-41]. Nutrients and food preference play important roles in the developmental rate and fecundity of organisms[42]. The development time of BSF is influenced by temperature, feed composition and rate of waste biodegradation[9].

The high productivity of BSF is indicated by the short TPOP, high survival rate and high fecundity. Long TPOP, low survival rate and low fecundity indicate low effectiveness of BSF production. Long larval periods can reduce their role as decomposers because there is no feeding activity at the non-larval stage[33]. The BSF reared on tofu dregs has a shorter TPOP, higher survival rate but lower fecundity compared with BSF reared on fermented maize straw[14], vegetable and fruit waste[6] and a mixture of wheat bran with chicken feed[33]. The age of first oviposition by females (APOP and TPOP) has an important effect on reproduction status on population growth[43].

In this study, the population parameter was analyzed by age-stage, two-sex life table. The result suggests when the population reaches the stable age-stage distribution and if there are no mortality factors other than the physiological ones, the BSF population reared on tofu dreg can multiply 23.95 times with an average of 43.705 days with an exponential rate of 0.0713 per day. This finding shows that tofu dreg was suitable as a potential growing substrate for BSF which can reduce tofu waste problems while providing a nutritious source of animal feed. However, the intrinsic rate of increase and finite rate of increase in this study were not different from the previous study which reared BSF on an artificial diet (wheat bran and chicken feed). Whereas, the net reproductive rate was lower and mean generation time was shorter at BSF reared on tofu dreg compared to the recorded of BSF reared on artificial diet[33].

The research reported here demonstrates that the reproductive value significantly increases at the time of adult females emergence. The BSF female individuals of ages 42 (counted from birth) make the greatest contribution to the population. The reproductive value is described as the contribution of an individual to the future population. The contribution of males to the future population is not defined, therefore there is no curve for males (Fig. 4). However, the reproductive value and fecundity of BSF in our study were much lower than in the previous study[6,33,34,44]. Females fecundity is influenced by the nutrient content available during larval stage[39,45] or by the composition of nutrition provided in adulthood[46,47]. In addition, a protein-rich diet during the larval period can increase the oviposition activity of female BSF[47]. The tofu dreg contains about 20.93% protein, 21.43% fiber, 10.31% crude fat, 0.72% calcium, 0.55% phosphor and 36.69% of other compounds[48]. The reproductive potential of BSF adults reared on tofu dreg may be improved by adding an extra protein source, according to Pastor *et al.*[49] which house fly (*M. domestica*) fed on two protein sources have an increased egg production. Research by Lupi *et al.*[46] and Bertinetti *et al.*[47] showed that a diet rich in protein or sugar would increase the lifespan and generate the opportunity to get the higher mating frequency and oviposition on adult BSF. Feeding activity on BSF only occurs during the larval period, thus it plays an important role in determining the intake and storage of nutrients needed for an adult stage to survive and reproduce. The quality of BSF biomass is highly dependent on the nutrient composition contained in the larval rearing substrate[50,51].

According to the findings reported by Gobbi *et al.*[37], other factors that influenced mating and oviposition behaviour of BSF is having sufficient light intensity, humidity and availability of oviposition media. Mating success of BSF required optimum light intensity, thus insufficient light on cloudy days may lead to the reduction of adult BSF productivity[52,53]. The BSF mating activities in the tropic area started at the age of two after eclosion up to 8 days in the morning when the weather warms up and peaks from 11:00-12:00 when daily sunlight intensity is at its highest[54]. The BSF mating success can be dramatically increased by exposure to light, particularly under the rich wavelengths near 440 and/or 540 nm and having irradiance with an appreciable fraction equivalent to the intensity of full sunlight[55].

Given the reproductive potential and survival rate of BSF in tofu dreg, we suggest more experiments should be directed to studying BSF in tofu dreg thus its reproductive potential and fecundity can be increased, possibly by providing extra high protein feed treatment or improving the adult stage maintenance system. It is also necessary to carry out further research on the life table of BSF reared on tofu dreg in different environmental conditions. As a result of the work to be done, it must be determined that the use of tofu dreg as rearing substrate in the production of BSF is more efficient and important which contributes to the recycling of environmental organic waste.

CONCLUSION

Based on the result, it can be concluded that BSF can survive and successfully produce offspring when reared on tofu dreg, therefore tofu dreg can be considered as a suitable growing substrate for BSF larvae. The two-sex life table analysis gives a comprehensive description of the stage differentiation of BSF.

SIGNIFICANCE STATEMENT

We think that this information would be useful and can provide a clue for rearing and studying on biological aspects of BSF on tofu dreg compared to other organic waste. These results can be used to develop waste management programs especially to solve the tofu waste problem. The life table data obtained in this study can provide insight into the population dynamics of BSF. Calculating age-specific birth and death rates of BSF maintained in a medium through two-sex life table analysis enables us to discern patterns and make predictions about future growth or decline in the BSF population.

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