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BLACK SOLDIER FLY *HERMETIA ILLUCENS* (L.): IDEAL ENVIRONMENTAL CONDITIONS AND REARING STRATEGIES

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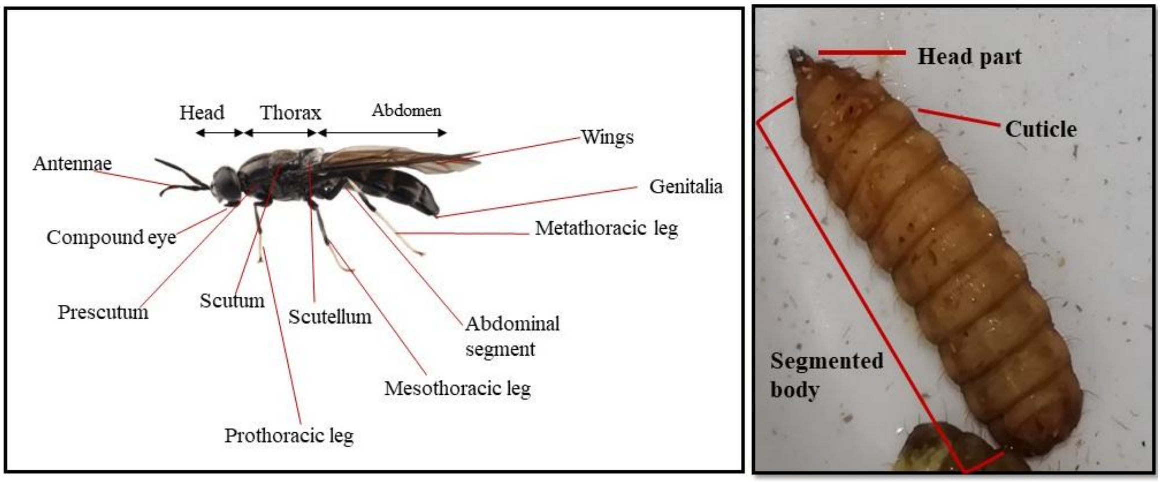
ABSTRACT

Endeavours to recycle organic waste by utilizing black soldier fly (BSF) *Hermetia illucens* (L.) into waste management and high nutrient biomass development have indeed picked up momentum recently. But there is not much data on their appropriate rearing conditions. Very few studies delineating the fecundity and reproduction capacities of BSFs concluded that the presence of natural sunlight or artificial light with intensity of 110-200 µ mol m^2s^{-1} and above triggers mating and oviposition (about 85-90%) at successfully higher rates along with ideal temperature (26 to 40°C) and relative humidity (40-70%) conditions. Optimum food moisture (50-80%) also plays a vital role in enhancing the consumption rate of waste and therefore the treatment efficiency of the larvae. Significant development of the BSF larvae and the treatment efficiencies were also observed to be governed by the pH of waste and the optimum range was defined to be of 6.0 to 9.0. The type of organic waste also equally influences the development, fecundity, and the lifespan of flies. The present review highlights the significant research that has been conducted with respect to lifecycle of BSFs, under the set of different light combinations (LED and fluorescent lights), temperatures and organic waste composites (protein rich and fat rich substrates). Conclusively, it was inferred that ameliorations in rearing conditions such as investigation of suitable light source, modifications in egg collection and hatching structures and knowledge of biology of flies can further boost the reproductive capability of fly thereby promoting successful insect rearing and mass production.

Key words: *Hermetia illucens*, mating, environmental factors, oviposition, lifecycle, mass rearing, organic waste, development time, survival rate, adult weight, life-history traits

Form the past few decades, black soldier fly (BSF) *Hermetia illucens* (L.), larvae have played a vital role in treatment of organic waste such as food waste, abattoir waste, animal, and human faeces, etc. embracing the prospects of circular economy worldwide. The larvae are also regarded as the impeccable source of proteins, lipids and carbohydrates supplementing the animal feed crisis (Tomberlin et al., 2009). Apart from this, bioactive compounds, degrading enzymes and antimicrobial peptides secretions within the species offers a tremendous outlook from industrial point of view. The larval extracts have now become of great interest as they make the insect mass rearing economically sound because of their inherent distinctive properties and pave the ways for development of antimicrobial compounds (Muller et al., 2017). Promoting the excellent breeding activity among species to recover huge quantity of eggs and thus the larvae are the most troublesome task to manage. Therefore, rearing the species demands the utmost care and improved technical skill especially dealing with the oviposition and mating events in the BSFs. In general, insects are ubiquitously distributed in environment based on their degree of tolerance, adaptivity and physiology (Dixon et al., 2009). Certain set of environmental conditions such as temperature, relative humidity, moisture, sunlight, and aeration are crucial factors for successful copulations among individuals of opposite sex, egg laying activities and successful mass production (Jarosik et al., 2004; Singh and Kumari, 2019). One such study stated that regions with wider temperature profile is highly favourable for insect development encompassing higher population comparative to the regions with smaller temperature profiles (Addo-Bediako et al., 2000; Deutsch et al., 2008).

Black soldier flies [BSF-*Hermetia illucens* (L.)] has the capability to thrive even under hostile conditions (Diener et al., 2011a) and has a typical life cycle of 1- 2 months. The basic anatomy of adult fly and the larvae is shown in Fig. 1. The larval stage is the



a. BSF adult b. BSF larval stage

Fig. 1. *H. illucens*- larvae and adult

only feeding stage wherein they feed voraciously on organically rich waste (Alvarez, 2012; Caruso et al., 2013; Barragen-Fonseca et al., 2017; Dormants et al., 2017). The longevity of adult flies may be significantly increased by providing the continuous water source (Myers et al., 2014; Hassan and Dina, 2019). The adult flies have single mating in their entire life span of 7 to 8 days. The number of eggs per clutch may vary between 300-500 or even more whereof the hatching occurs after 3-4 days of mating (Sheppard et al., 2002; Park, 2016; Sharanabasappa et al., 2019). The larval development takes about 13-16 days under optimum environmental conditions however, it may last for 24 to 30 days under unfavourable conditions. Pupation of adult flies takes about 5-14 days and the cycle of mating and egg hatching starts again initiating the next cycle (Yu et al., 2009; Pathak et al., 2015; Barragen-Fonseca et al., 2017; Win et al., 2018; Sharanabasappa et al., 2019). The physiological differentiation between male and female is made on the basis of the appearance of their genitalia otherwise both of them looks similar from naked eyes (Oonincx et al., 2016).

Many researchers have meticulously studied the life cycle of BSFs in order to develop skills to significantly enhance the reproduction rate, larval development and survival of the flies. Notably, BSF larvae has been certified as animal feed for poultry animals and fishes because of its high nutritive values such as protein content in between 40-50% and fat being 25-40% of the total dry weight of BSF larvae (Renna et al., 2017; Gasco et al., 2019). Despite that, it also contains huge amounts of fatty acids, micronutrients, and other essential nutrients (Nowak et al., 2016; Spranghers et al., 2018). Different controlling factors such as substrate moisture level, ambient temperature conditions, suitable light exposure and intensities have also been investigated many times and still is an ongoing activity demanding the unique consideration to develop skill and promote mass rearing (Sheppard et al., 2002; Tomberlin et al., 2009; Holmes et al., 2016; Cammack and Tomberlin, 2017). The pioneer studies of Sheppard et al. (2002), Tomberlin et al. (2009), Holmes et al. (2012) and others have also defined that the ideal rearing conditions for of BSF larvae are as follows; i) temperature should be ideally between 26-27°C based on time taken for development, larval and adults' survival, ii) relative humidity should lie in between 60-70% and iii) optimum moisture levels in the substrate should be between 40-85% wherein the larval development is highest at moisture levels between 40-70%, oviposition is highly significant at 40-60%. Humidity levels below 30% causes larval dehydration and egg desiccation (Holmes et al. 2012). However, the favourability of environmental conditions may vary with varying climatic zones since the species has a cosmopolitan distribution ranging from tropical to temperate regions (Ustuner et al., 2003; Martínez-Sánchez et al., 2011; Tsagkarakis et al., 2015) and consequently the outcomes may be varied.

The present review describes the suitable range of environmental factors for BSF rearing such as temperature, relative humidity, moisture, light and pH. It also compiles the findings of previous studies related to rearing strategies in order to study life cycle of BSF in response to different light source and exposures, different temperatures and organic waste having different nutritional composition. Learning such skill of BSF rearing would be promoting enhanced mass rearing of BSF which will further facilitate its utilization for organic waste treatment and other societal benefits.

1. Environmental factors

Mating among opposite sexes of BSFs is strongly under the control of surrounding temperature, substrate properties and moisture content. Not just this, the natural conditions (relative humidity, sunlight) contribute towards ideal egg laying and incubation events and the larval development. Besides that, substrate selection also equally contributes to the successful eggs laying and hatching activities since the females prefers to lay eggs near to the food source with strong putrescence (Tomberlin and Sheppard, 2001; 2002).

Ideal thermal conditions (temperature) and the relative humidity: Earlier studies have concluded that about 99% mating and oviposition occurs in the temperature range of 27.5 to 37.5°C combined with 60% relative humidity (Sheppard et al., 2002; Holmes, 2010). In a similar setting, 50-90% relative humidity has been defined as the ideal condition for enhancement of BSF rearing at research centres in temperate regions according to different group of others (Diener et al., 2009). So also, Tomberlin et al. (2009) found significant development of males and females at 27°C± 2 however at higher temperatures (30-36°C) smaller males and females were observed in the study and life expectancy was also decreased. On the other hand, it was noticed that temperature and humidity can have genuine impacts on egg eclosion and development at different stages if not looked after ideally (Park, 2016). Holmes et al. (2012) additionally reasoned that less than 25% relative humidity can have higher parching rates and higher mortality of species. In the context of eggs hatching, the lower humidity levels cause moisture loss from egg membrane leading to desiccation. A humidity level as low as 25% results in higher desiccation and mortality rates whereas at 70% and above, adults live longer, and the eggs retains the proper health conditions. More precisely, relative humidity between 70-90% provides the absolute conditions for mating and oviposition activities mediated by the adults in combination with 27°C temperature of the surrounding air (Holmes et al., 2012; Park, 2016). Chia et al. (2018) also stated in his study, that presence of optimum temperature conditions improves the fertility and fecundity rate of adult flies.

Substrate moisture levels: The development and endurance of the species is exceptionally affected by the moisture of the feed (Cheng et al., 2017). Numerous researchers have peculiarly identified that the unnecessary moisture levels (more than the optimum levels) in the feeding substrates can impact feeding rate and might result in the development of thick and clumpy material causing trouble in further handling (Diener et al., 2011b). Another group of researchers have reasoned that 80% moisture content in the feed is ideal for BSF development (Cheng et al., 2017; Dortmans et al., 2017). Similarly, Barragan-Fonseca and her co-workers defined that the moisture level in between 52-70% are the most suitable conditions for proper larval growth and development (Barragan-Fonseca et al., 2017). Comparable results were likewise referenced in the investigation of De Smet et al. (2018) where a moisture level underneath 40% was unfit for development of the flies at various stages therefore influencing the fecundity rate or the mating in the files.

Optimum light exposure and intensities: In general, different parts of an insect's eye have different spectral sensitivity and the spectral sensitivity functioning may differ among species. The ommatidia are the structural unit of insect's compound eyes and have photoreceptor cells arranged in different fashion. Most of the insect species have the light sensitivity lying in the range <300 to >700 nm. They don't see the light past 700 nm, a light source with corresponding wavelength between 450-700 nm is ideal for reproductive activities in adult flies (Briscoe and Chittka, 2001; Zhang et al., 2010). The visual pigment or photoreceptors in insect eyes is composed of chromophore and opsin protein which interacts with light sensitivity of shorter or longer wavelengths (Peitsch et al., 1992; Stavenga, 1992; Cronin et al., 2000). Similarly, BSFs have photoreceptors belonging to a specific class which is highly sensitive to UV light (367 nm) and blue light (440nm). Ventral part of eye was maximally sensitive to blue light whereas dorsal retina was sensitive to blue green (504 nm) and UV light has additional peak in both ventral (40%) and dorsal retina (20%) (Fig. 2) (Oonincx et al., 2016).

For successful mating in BSF, direct daylight is assumed to be significant in the common habitat and this is the explanation that huge mating doesn't happen in winter seasons however creating a similar warm environment may promote high mating activities. Studies considering the indoor investigations on BSF require artificial light source. About 85% mating events happen within the sight of common daylight with an intensity of 110 µmol m^2s^{-1} however the mating rates decreases below that (Park, 2016). Previously, Briscoe

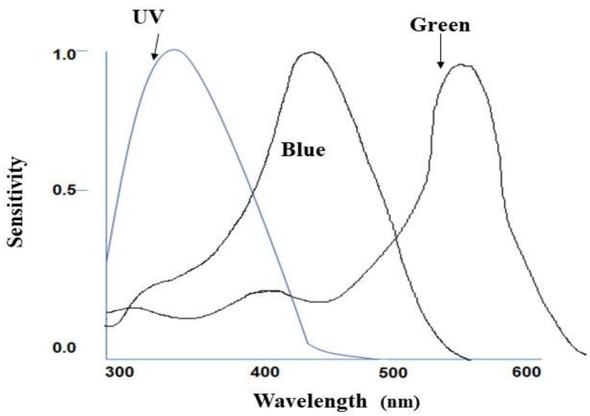


Fig. 2. Spectral sensitivity of compound eye (retina) of *H. illucens*

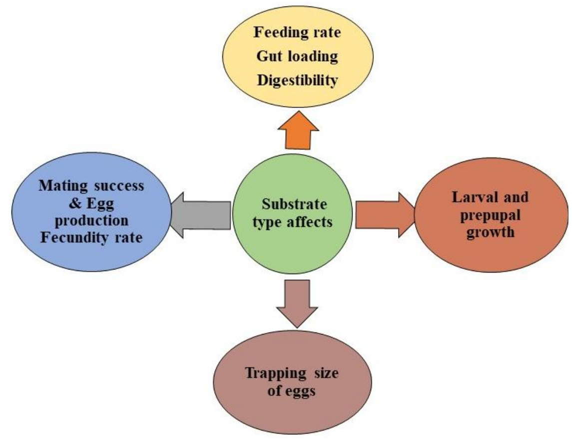


Fig. 3. Substrate effect on different traits of *H. illucens*

and Chittka (2001) also stated that a 500-watt quartz iodide lamp with an intensity as high as 135 µmol m^2s^{-1} was able to promote the mating and oviposition at rates similar to those observed in the presence of natural sunlight. Similarly, in another study, artificial light source was accounted to have effect on mating wherein the mating and oviposition of the species was associated with the utilization of Quartz-iodide light (61% efficiency) with the same intensities as the counterfeit light source as compared to natural sunlight and rare earth lamps (Zhang et al., 2010). This specific strategy can be extremely worthwhile and compelling for raising the species outside their local natural surroundings, where daylight is the principle affecting source. Besides that, Tomberlin and Sheppard (2001) have also reported that lekking behaviour among male and females is restricted by the type of habitats, *for instance*, males aggregate near bushy areas establishing the territory which serve as the attractant for females and initiating the mating. Notwithstanding, to have better comprehension of science of species affected by light and other factors as discussed above, extra research is required to significantly promote the mass scale rearing of the insect (BSF).

Effect of substrate: The substrate (diet) composition has been extensively studied worldwide to raise BSF however due to their diversity to eat any kind of waste (food waste, poultry waste, animal faeces, human faeces, animal waste, etc.) such problems are not usually encountered (Boykin, 2019). But still, the substrate composition is equally influential for the healthy profile (nutritional aspects) and development of life history traits of BSF (Sheppard et al., 2002; Tomberlin et al., 2002; Boykin, 2019) because it affects the feeding rate and conversion, the gut loading and digestibility (Fig. 3). For instance, larvae prefer to consume food with high fat content (Nguyen et al., 2015). Moist diet is preferred by the BSF unlike the other insects such as mealworms (Tomberlin et al., 2002). Similarly, the high protein or highly fibrous food often lowers the larval or prepupal growths, the mating behaviour, and the eggs resilience (Tschirner and Shimon, 2015; De Smet et al., 2018). Regardless of that, the higher larval development was likewise seen in the neonates fed with plant-based substrate when contrasted with animal-based diet since they harbour microorganisms delivering plant processing enzymes (Liu et al., 2008; Tomberlin et al., 2009; Manyara, 2018). In one such study of Chia et al. (2018), considering the mating and eggs production, it was found that heavier prepupae were obtained in the treatment where the larval were fed with Brewer's spent grain supplemented with Brewer's yeast (nutritionally balanced diet).

Danieli et al. (2019) also suggested that a mix of different by-products of food such as alfalfa, barley, and wheat by products are remarkable source of feed for enhanced larval development enhancing the nutritional accumulation and survivorship of the BSFs. He also added, diet should be fat enriched instead of protein or carbohydrate rich substrates because the latter two can negatively affect the rearing and overall development. In addition, Ewusie and his co-workers, also determined that the type of substrate affects the trapping size of egg clutches of BSF in combination with the other environmental factors. In their study, among the piggery, sheep, and poultry waste, the piggery waste was the most influential (Ewusie et al., 2019).

pH: A concern for pH effect on BSF development and survival has been also raised by Green and Popa (2012). Larvae were found to regulate a pH of 9.0 occurring in leachates or other substrates (Green and

Popa, 2012). Similarly, the increased larvae growth and heavier pupal mass can be positively correlated with substrates having pH in between 6.0 to 10.0 however; a greatly reduced development is seen at pH below 2.0 (Ma et al., 2018). In one such recent study, in which the researchers examined the effect of pH and the feeding system on BSF larvae found that initially for a week pH significantly affected the larval weight however at the end it was same at all pH between 6 to 9 under the environmental conditions of 29.3± 1.4°C temperature and 70.0± 5.0% relative humidity. In fact, the larval feeding activity also modifies the pH of the feed in between 8.9 to 9.4. But, larval and pupal weight, pupation rate, sex ratio survival and mortality rates were majorly influenced by the feeding system (Meneguz et al., 2018).

2. Rearing

Effect of temperatures and substrate types: Upkeep of appropriate ecological conditions has always been the chief significant thing to effectively manage the mass rearing activities of BSF. In the similar context, researchers are trying their best to introduce best suitable conditions to manage the species to offer secondary solution for the public and the concerned people i.e., the waste management and its valorisation. One of the more recent study examined the effect of different ecological factor (i.e., temperature, relative humidity, and substrate moisture) on different life history traits of BSF in which the baiting material used for trapping adult flies included a mix of manures of chicken and rabbits, food and household wastes. The development was monitored for different array of temperatures (10 to 42 °C) combined with relative humidity between 70 to 72% and 12:12: Light: Dark photoperiod. The population growth rate was highest in treatments as compared to controls (without Brewer's yeast). The authors concluded that the number of successful mating and fecundity rate can also be correlated with pupal mass of insects. The temperatures below 15°C and above 40°C was found to negatively impact the survival of the fly at all stages resulting in extremely high mortality rates. The findings of Chia et al. (2018) have been shown in Table 1. Likewise, Shomu et al. (2019a; 2019b) also published work closely related to the study of Chia et al. wherein they examined the effect of temperature and substrate type (brewer's spent grain and cow dung) on the growth, development, and survival of BSFs and mating rates in adults. The findings stated that the development was faster for the larvae fed with brewer's spent grains as compared to cow dung and the optimum range of temperature suitable for BSF was 25-30°C. Srikanth and Sharanabasappa reported that kitchen waste was significantly superior obseved

Table 1. Effect of temperature on life history traits of *H. illucens* (Chia et al., 2018)

S. No.	Light history traits	Temperature	Days	Survival rate (%)
1.	Egg eclosion	15°C	14 (both D1 and D2)	Highest at 35°C (75% and 30°C (80%) for both D1 and D2
		35°C	2.60(both D1 and D2)	-
2.	Larval development	15°C	13.14 (both D1 and D2)	-
		30°C	62.4 (both D1 and D2)	-
3.	Prepupal development (Failed at 40°C)	15°C	83-86 (both D1 and D2)	-
		30°C	8-10 (both D1 and D2)	-
4.	Larval to adult development	15°C	184 (D1); 181(D2)	-
		30°C	28 (D1); 31(D2)	-
5.	Oviposition period	20°C	16 (both D1 and D2)	-
		35°C	5 (both D1 and D2)	-
6.	Larval survival rate	-	-	92% (35°C); 90% (30°C); 28% (40°C) for both D1 and D2
7.	Prepupal survival rate	-	-	83% (25°C) and 82% (30°C) for D1; 79% (35%) and 77% (30°C) for D2
8.	Pupal survival rate	-	-	77% (30°C) and 5% (37°C) for D1; 75% (30°C) and 20% (37°C)
9.	Adult survival rate	Decreased with increase in temperature from 15°C to 37°C with increased fecundity at higher temperatures		

D1: BSGs with brewer's yeast; D2: BSGs without brewer's yeast (control) with maximum larval (0.22g/ larva) and pupal weight (0.20g/ pupa). The Fecundity was observed to be 698 eggs/ female when reared up to 14 day, significantly the maximum amount of feed consumed was 18100g in 20days, feed conversion ratio (97.37) was maximum in mixed vegetable waste.

The selection of substrate should be wise as it effects both the physiological and morphological development (gonads development, sex ratio, mortality, duration of different stages) of both neonates and the adult flies. Gobbi et al. (2013) testified the insect's development against three different diets i.e., hen feed, fish meal and a mixture of both. The larvae fed with fish meal and mixed diet showed the prominent growth and development than the larvae fed with pure meat meal (Gobbi et al., 2013). Notably, till date various examinations have been set up testing the effect of various sorts of organic waste on life history attributes of BSF and their performances, for example, larval growth and development, pupal development, adult weights and lengths, longevity, and the endurance. Similar in case, the investigations of Tomberlin and Sheppard (2001), Diener et al. (2011b), Gobbi et al. (2013), Nguyen et al. (2013), Li (2014), Oonincx et al. (2015a, 2015b) and Srikanth and Sharanabasappa, (2021) have affirmed the BSFs against various natural substrate to assess diverse life stages. Table 2 has compiled the studies on life history traits of BSF fed against variety of organic diets having different nutritional contents which was originally combined in the studies of Barragan-Fonseca et al. (2017) from the studies executed up until now. The abiotic conditions were as follows: temperature- 27± 2°C; relative humidity-70± 10%; food moisture- 66± 4%. Interestingly, a conclusion was also drawn that the availability of abundant food positively affects the larval growth and development however, the waste reduction efficiency is greatly reduced (Liu et al., 2008; Diener et al., 2009; Banks, 2014).

Harden and Tomberlin (2016) also deeply investigated the synergistic effect of temperature and diet on BSF development. A mix of grains (corn meal, wheat bran and alfa alfa), beef and pork meet were used

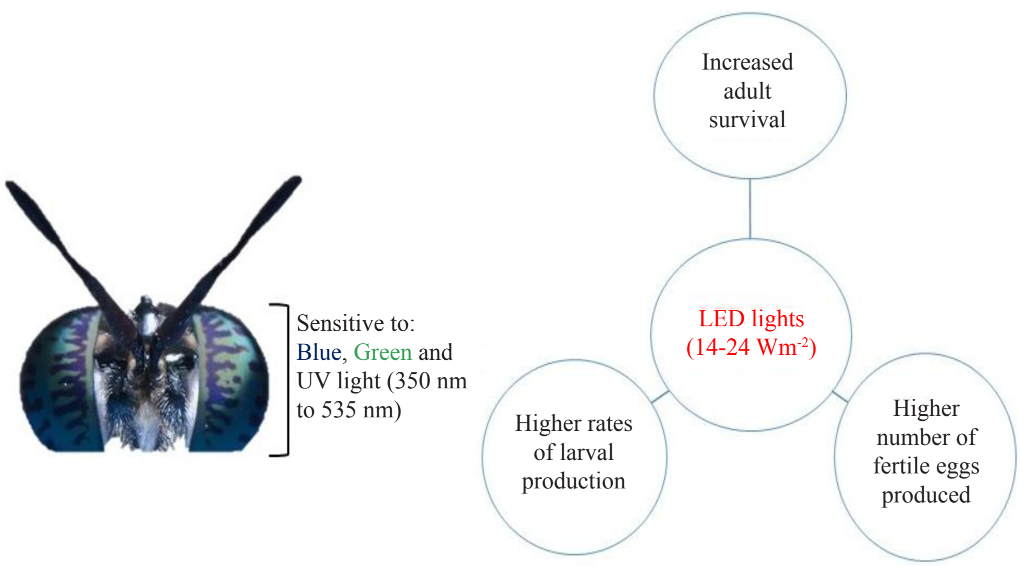
Table 2. Life history traits and performance of *H. illucens* larvae fed with organic waste

S. No.	Life history traits (Mean± SD)	Organic waste			
		Chicken feed (or feed with similar nutrient content i.e., Protein~14%; Fat~4%)	Meat waste	Faeces	Vegetable waste
Larval stage					
1.	Development time (days)	24.6± 6.2	32.5± 8.2	27.5± 3.8	34± 13.5
2.	Survival rate (%)	89.4± 9.4	48.2± 8.7	89± 7.5	78.9± 13.2
3.	Fresh matter (FM) weight (g)	0.158± 0.02	0.158± 0.0	0.17± 0.03	0.13± 0.03
4.	Dry matter (DM) weight (g)	.044± 0.0	-	0.031± 0.02	0.028± 0.01
5.	Larval dry matter (DM) content (%)	36± 1.8	-	-	36.3± 2.5
Prepupal and pupal stage					
6.	Pupal development time (days)	14.8± 6.8	16.5± 7.5	17.8± 3	22.9± 1.2
7.	Fresh matter (FM) prepupal weight (g)	0.105± 0.005	0.115± 0.01	0.193± 0.08	0.179± 0.03
8.	Dry matter (DM) prepupal weight (g)	0.037± 0.004	-	0.018; 0.04	0.071± 0.01
9.	Fresh matter (FM) pupal weight (g)	0.150± 0.03	-	-	-
Adult stage					
10.	Adult weight (g DM)	0.021± 0.0	-	-	-
11.	Adult weight (g FM)	0.053± 0.01	-	0.046± 0.01	-
12.	Adult length (mm)	15.8± 0.0	-	-	-
13.	Adult longevity (days)	9.4± 0.2	-	12.5± 2.1	-
14.	Total cycle (days)	40.2± 6.4	-	-	-

as the diet source and the temperatures conditions were between 29-33°C and average relative humidity was 71.0± 16.3%. They found that eggs development was not significantly affected with variations in temperature. However, larval length and development was affected notably with temporal variations and was highest at 32.2 and 27.6°C. Moreover, about 23.1%- and 139.7% more-degree hours were required to complete the larval development fed with pork diet in comparison to beef and grain-based diet. Comparatively, larval development fed with grain diet was inconsistent when assessed with the age of field larvae and the pork and beef based larval development were appreciable.

Effect of light: Oonincx et al. (2016) and Nakamura et al. (2016), studied LED expand based radiance on indoor reproduction rates and the oviposition periods. The former study included the photoreceptor spectral sensitivity of the compound eyes of BSF while the latter investigated the oviposition and survival rates under natural sunlight supplemented with LED irradiation. Oonincx et al. (2016) found that the ommatidia of BSF contains photoreceptors cells sensitive to blue, green and UV light having trichromatic visibility; therefore, the LEDs based illumination significantly increased the egg clutch yields resulting in higher larval production comparative to fluorescent tubes (control) (Figs. 4, 5). Similarly, small cage (27 x 27 x 27 cm) study of Nakamura et al. containing 100 adult flies (50 male and female each) in each implied similar patterns of oviposition in both LED illumination and natural sunlight however the number of fertilized eggs obtained were higher under the effect of natural sunlight in comparison to LED illumination. The oviposition was considerably increased from 4 to 17 days. Examining the sugar solution treatment and water treatment it was observed that the longevity of adults (3 times in males and 2 times in females) increased when fed with sugar solution comparative to water alone (Nakamura et al., 2016). The findings also concluded the absence of mating below 69 $\mu mol\ m^{-2}\ s^{-1}$ and highest at 200 $\mu mol\ m^{-2}\ s^{-1}$.

Heussler et al. (2018) scrutinized the impact of three different artificial light sources (LED green, fluorescent lamp, and halogen lamp) on the life history traits (oviposition and half-life) and mass production of BSF where the larvae were reared in a plastic box under the environmental conditions at 27°C temperature and 60% relative humidity respectively. He also encountered the similar observations for oviposition as in above-mentioned studies. Three replications were made for each light source with intensity of 59 $\mu mol\ m^{-2}\ s^{-1}$ in different cages having a light: dark photoperiod of 16 and 8 hours. Mating and oviposition rates were found similar in all the three conditions where the peak was observed from 4 to 8 days of emergence however the half-life of both males and females significantly reduced. Shorter half-lives of adults were observed under halogen light conditions as compared to LED



a. BSF compound eye sensitivity for LED illumination

b. Effect of LED illumination over control (fluorescent light)

Fig. 4. Diagrammatic representation of photosensitivity of *H. illucens* and effect of LED illumination on adult survival and larval development (Oonincx et al. 2016)

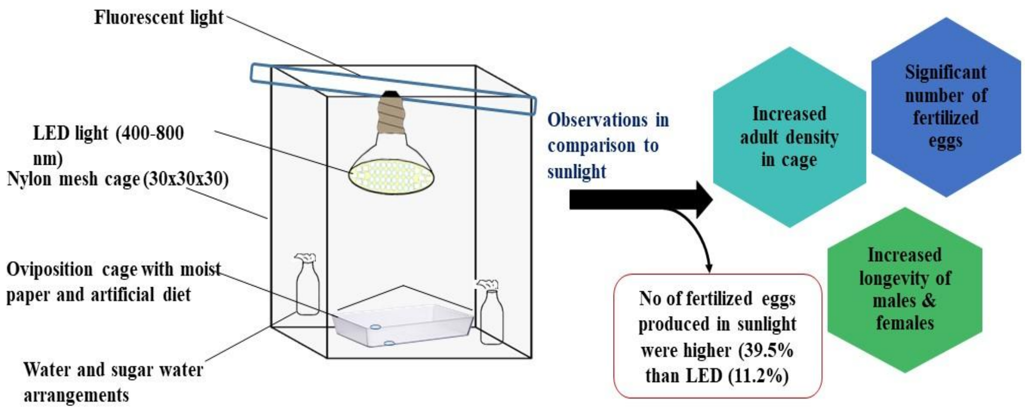


Fig. 5. Schematic view of effect of LED illumination on egg production and adult longevity and survival in *H. illucens* (Nakamura et al., 2016)

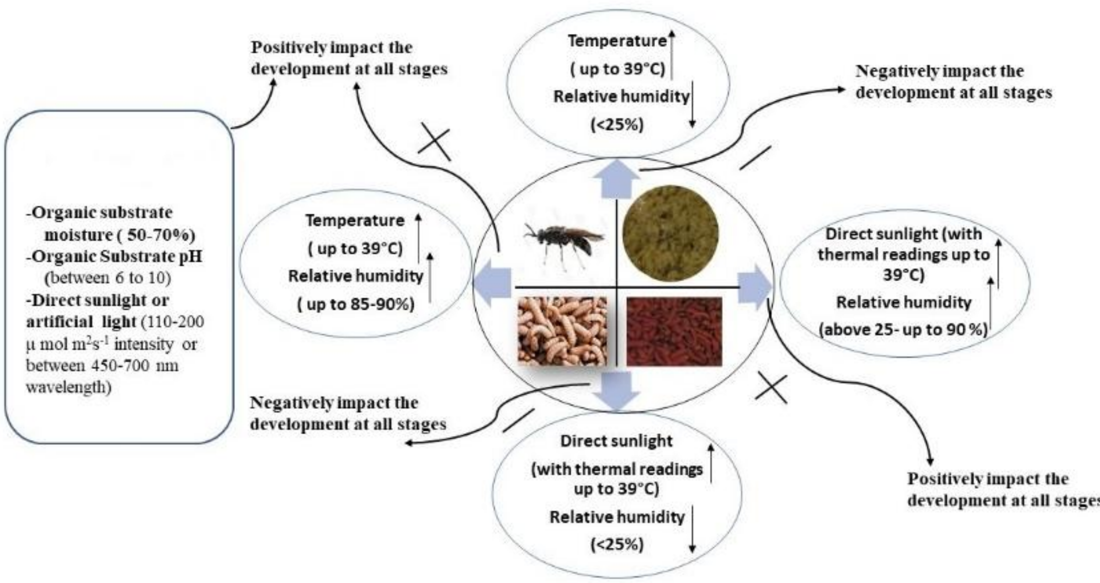


Fig. 6. Different set of environmental conditions ideal for BSF development

illumination lasting from 6 to15 days for males and 3 to 13 days for females. The authors also concluded, the shorter half-lives of adults in Halogen light may be due to unsuitably higher temperature and excess heat generation. Attiogbe et al. (2019) also applied the similar microclimatic conditions to achieve maximum mating, suitable oviposition and larval development in order to get higher efficiency towards mercury contaminated waste wherein direct association between larval density and reduced mercury content from waste was observed.

In the similar context, Boaru et al. (2019) described that suitable oviposition structures improves the reproductive process of adults in captivity. The study included four different types of cage structure for oviposition or egg laying sites i.e., wood cages, glass cage, corrugated cardboards, and plastic material along with similar microclimatic conditions (22-28°C temperature, 40-60% humidity and 8 hours of artificial light exposure) and the substrate (brewer's grains). In all setups over 98% of adult emergence were recorded and maximum amount of egg masses was found in experimental cage made up of wood followed by corrugated cardboard, plastic structures, and glass structures wherein each cage was populated with 50g of pupa at the start of experiment (Boaru et al., 2019). Based upon the findings of different studies the range for different set of environmental conditions ideal for BSF development is shown in Fig. 6.

3. Cooccurrence of house flies while rearing BSF

While rearing, co-occurrence of houseflies along with BSFs is also very evident and need to be discussed as it impacts the waste conversion efficiency and the insects' growth. Though the BSF are reported to repel the housefly oviposition yet the experimental areas established for BSF rearing and mass production often experiences the presence of house flies ensuing competition for the available substrate. In one such study (Miranda et al., 2019), no BSF pre pupation occurred in the treatment (pig manure) inoculated with house fly larvae at initial stages and reached maximum pupation when reared alone on the fresh pig manure. In addition, the negative impact on BSF growth was also attributed to the presence of houseflies and age of resource. Similarly, Hassan and Dina (2019) also encountered the co-occurrence of a total of 3554 insects including the BSF where the fermented coconut waste was used as egg laying sites in plastic bins. BSF larvae were highest in number in oviposition media but *Drosophila melanogaster* and *M. scalaris* also have significant counts in competition to BSF.

CONCLUSIONS

Black soldier flies have been performing outstandingly well to deal with the concerns of waste management and feed supplementation. Correspondingly it demands the thorough knowledge on specific tolerance limits of BSF towards ecological conditions. It was concluded that BSF growth and development is directly influenced by temperature and the diet composition serving to be the most crucial factor in environment. The temperature and relative humidity largely control the insect development, daily cycles, and seasonal variations and affects the biology of insects, their survival, life span, reproduction rate, population growth parameters and the sex ratio. Optimum light conditions, humidity also equally contribute to the insect's physiology, behaviour and morphological traits. Moreover, wood based, and plastic material-based egg hatching structures may serve as the better oviposition sites and mass egg production in comparison to other conventional setups. However, it should be emphasized that breeding activity is largely influenced by the specific environmental conditions.

Further, intensification of fecundity rate in BSF under indoor environment requires appropriate investigation of suitable light source and intensities which may effectively enhance the mating rates, egg production and thus other life history parameters. In addition, there is a need to examine how to improve the reproductive capacities of the flies for a progressive proficient raising at the study sites. Future research ought to build up extra models for distinguishing improvement of every instar, which may help in improving the exactness and accuracy of larval age gauges which would serve for other important purposes such as sustainable and environmentally sound management of organic waste as it outshines the present conventional techniques in several ways (less time for composing, higher efficiencies of waste reduction, carbon sequestration, pathogen control).

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