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Technical Feasibility of *Hermetia illucens* in Integrated Waste Management, Renovated with Sewage Water, an Overview

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Abstract

In last one decade, numerous researches have been performed on the Black Soldier Fly (BSF) larvae to establish the optimal breeding condition in contradiction of the computational temperature, wide sort of substrates and sub optimized feeding ratio. Even though the considerable number of methods has been already established and supervised, there have been a technical lagging always been predominantly in the form of egg hatching rate, moisture tolerance, drainage and rearing requirements to categorize the obtainable alternatives. In order to inculcate the reimbursements of the existing technology and fulfil the knowledge gaps pertaining, in this paper, we propose a monitoring based real time hatching system which comprises the technicality and precious management skills. This review emphases a comprehensive nutrition technique for BSF larvae by means of different fodder acclaim abilities in association with the adaptability of sewage water and accentuate the change in the behavioral characteristics of the adult as well as on larvae stage, which can open a new economic window in sustainable waste management technique and will be capable of addressing multi-dimensional solution in the form of green and novel alternative.

Subject Areas

Environmental Sciences

Keywords

Hermetia illucens, Bioconversion, Biodiesel, Manure, Protein, Sewage Treatment

1. Introduction

The requirement of formulating an alternate and sustainable waste management strategy for Chidambaram provokes the idea of using the Black Soldier Fly Larvae (BSFL) composting. Rather than the waste treatment and minimization, the above process is also capable of addressing multidimensional issues such as rising demand of implementing renewable fuel, increasing protein in farm and aquatic diet, yielding compost with high nutrient content, etc. The larvae of Black Soldier Fly consume the organic fraction of the waste ravenously and build a body composition with the higher amount of protein and fat contents. The protein content of the larvae generally used as a crude source of protein which replaces the expensive conventional protein source in pet food, poultry feedstock, fishmeal, etc. and the body fat has been successfully converted into value-added co-products such as biodiesel, grease, etc. Other major advantages comprise higher consumption rates and faster rate of degradation and bio-conversion [1] [2]. Trinh *et al.* [3] performed experiments on nutrition conditions with different substrate sources and reported the larvae were capable of degrading the wide range of wastes such as control poultry feed, pig manure, kitchen waste, fruits, and vegetables, etc. But the optimum reduction was observed in the case of poultry manure which yields healthier black soldier flies with lower mortality rates. Diverse rates and the relation between conversion efficiency and larval growth have been recorded by several researchers. But, in order to sub-optimize the value of these two key factors of BSFL composting, experiments have been conducted by feeding the larvae with four different concentrations of dairy manure to predict its influence on the life cycle traits of larvae as well as adult files to establish a relation between supply rate and BSFL growth [4]. The results reveal that the feeding rate has major impacts on larval and adult fly development and nutritional profile and it showed a proportional relationship in which larvae with greater substrate availability weighed more than those fed significantly lesser ration. Collaterally, Stefan *et al.* [5] stated that an average pre-pupation rate of 252 g/m^2/day (wet weight) was achieved under optimized environmental conditions and the bio-conversion yield around 65.5% to 78.9% depending on the quantity of waste added on regular basis and also by the availability of the drainage facilities. Stefan *et al.* [6] have observed that the optimal balance between treatment efficiency and biomass population can be maintained by a proper nutritional diet and feeding rate on a day to day basis, spiked by a moisture content of 60%. The above study also observed the rate of biomass production for different sorts of substrate and stated that an individual waste stabilization component can produce a pre-pupal biomass of 145 g (dry mass) per m^2 on a regular basis. Contradictorily, Myers *et al.* [7] have encountered significantly lower conversion rates. A bio-kinetic study was conducted to understand the correlation between the growth kinetics and feeding rate and stated the reduction in weight of dry matter varied inversely proportional to the waste loading rate. They observed in a lab-scale study when the larvae fed 27 g of waste on regular basis it reduced the dry fraction approximately by 58% while the other experiment yields considerably lower conversion rates (*i.e.* 33%), where larval feeding rate was increased by 70 g of waste matter/day. The increased larval feeding rates also found contradictory in the case of life cycle studies, it accelerated the mortality rates to 29% from 17% among larvae. Researchers have also worked on the degradability of the pharmaceuticals and pesticides by using BSFL and stated that, though the substances like roxithromycin, carbamazepine, propiconazole etc. fall under the category of hazardous waste, fly larvae composting minimized its degradation period by half and there was no bioaccumulation distinguished in the larvae [8]. In another study Ateng *et al.* [9] have taken cassava peel wastes and used it as fodder for BSFL, they have conducted the experiment with 200 of infant larvae, which were fed on the above-mentioned substrate with a deviation of 12.5, 25, 50, 100 and 200 mg/larva/day, the experiment results indicated an inversely proportional correlation between feeding rate with efficiency of feed conversion and optimal bio-conversion was observed at lowest feeding rate. Apart from this conventional feedstock, the technique is also capable of addressing awfully complex secondary wastes such as bio-leachate, persistent pollutants etc. A study undertaken by Diener *et al.* [10] investigated the impact of heavy metals on BSFL and reported that, the organic fraction of the municipal waste in developing and underdeveloped countries very often contains persistent pollutants because of lack of source segregation practices, which includes heavy metals like Cd, Pb, Zn etc. which may further cause bio-accumulation problems in the larvae and prepupae and subsequently enter into the food chain to cause biomagnifications. But the above study suggested that all the heavy metal elements were considered insignificant on the behavioural characteristics and life cycle assessment studies of BSFL and its impact was nullified by the immunity system of the larvae. On the other hand, Radu *et al.* [11] have taken the study on bio-leachate processing by using BSFL and stated that, the larvae of the black soldier fly is capable of degrading bio-leachate generated during the treatment period while feeding and growing off on it. The study also claimed that it depletes the COD level of composite leachate comparing to that leachate sample which was not exposed to the larvae. It also neutralized the acidic nature of the leachate and nullifies the impact of other organic pollutants such as VOA, Alcohols, and Amines etc. Numerous researchers also claimed the feasibility of BSF larvae in public health and sanitation engineering. Ian *et al.* [12] studied the capability of BSF larvae against the concentrated black water and stated that BSFL are capable of degrading human faecal matter and appreciably well-built larvae and the pre-pupae structure was observed for those larvae, which were fed single lump quantity of faeces. On the other hand, the larvae which were fed increasingly every 2 days, yields meagre pupation rate and results in the reduced body mass index. The researchers have observed optimum bioconversion and major effective feed conversion rate as 16% - 22% and 2.0% - 3.3% respectively, took place in groups, containing 10 and 100 larvae. This comprehensive management ability helps the treatment to emerge as a wholesome alternative [13]. Hang *et al.* [14] studied the economic feasibility of the above technology and reported; raw swine manure can yield up to 95 - 120 kg of larval population per m^3 of waste supplied to the system. The study also claimed that the live and fresh biomass can be served as an optional animal diet, rich in protein and fat content. As well as it is feasible in capturing the nutrients from the waste stream which can be further utilized as agro-based plant manure and the bioconversion technique stabilizes the primary pollutants and minimizes the production of obnoxious gases and odour formation by 94.5%. The larval composting has also proven to be effective against the removal of *Escherichia coli* with an index range of 92.0% and successive reductions were observed by the same researcher in total weight, total Kjeldahl nitrogen and moisture content in stabilized waste around 67.2%, 76.0% and 80.0%, respectively. The economic proficiency of the above technique even makes it more feasible with the yearly profit rages from US $33.4 - 46.1 per m^3, observed during the operational period. In order to interpret the above scenario an experimental study conducted by Tschirner and Simon [15] may be considered as a benchmark. They have investigated the influence of different growing substrates on the crude nutrient and they observed the impact of different fodder consumption on the larval body composition. They reported the yield of different nutrients for the experimental period of 15 day, where protein and fibre value ranges around 0.93 and 0.43 kg of wet mass, respectively. They also reported the changes in protein content due to the different substrate consumption, which showed the crude protein content values of 37.2%, 44.6% and 52.3% of dry matter, respectively. In this context a baseline by Li *et al.* [16] reported that synthesis of value-added co-products such as grease; biodiesel etc. is technically feasible, utilizing dairy manure as substrate. The extraction of grease from BSFL was performed with the help of petroleum ether, and thereafter biodiesel could be extracted in a similar manner with a two-step method. At last the remaining fraction of the manure could be anaerobically hydrolyzed to produce sugar. In their study, roughly 1248 g raw dairy manure was converted by 1200 larvae into 273.4 g compost material in 21 days. Once the stabilization got over approximately 15.8 g of biodiesel was obtained from 70.8 g dry BSFL, while 96.2 g sugar was produced from the anaerobic digestion of treated dairy manure. After completion of grease extraction, the residual dry fraction of the larvae was used as a potential source of protein-rich food staff for the animals. The larvae also showed potential against pathogen removal, a study conducted by Qiaolin *et al.* [17], reported the ability of BSFL for *E. coli* reduction from dairy manure and they introduced the larvae into 50, 75, 100, or 125 g sterilized dairy manure homogenized and inoculated with *E. coli* and stored for 72 h at 27˚C. They concluded that the larvae composting potentially decreased the *E. coli* count in all the respective conditions. Not only this, pronto the black soldier fly larvae have been acclaimed as the most apposite alternative to the costlier commercial animal protein sources. Nyakeri *et al.* [18] has reported a complete nutrition profile; the researchers have performed experiments such as proximate analysis for vitamins and minerals and concluded that wild *Hermetia illucens* larvae consist approximately 40% protein, 33% crude fat, 12% crude fibre, 15% ash and remaining all sort of trace elements such as manganese, sodium, iron, potassium etc. It also includes the different variety of proteins namely, thiamine, riboflavin and vitamin E etc. The similar body composition was reported in another successive study conducted by Sara *et al.* [19], who worked on the protein synthesis aspect and concluded that the protein extractability of larval flour fraction segregated was around 36% crude protein and 60% crude fat respectively. The further improvement in the protein quantity recovered was done by defatting operation and it yields increment in crude protein content by 47%, while depleting the crude fat content by 8.8%. The above nutrition profile of the black soldier fly larvae designated its ability, hence it should be considered as a potential and cheap alternative protein source. Consistently, Thomas *et al.* [20] also stated that due to the greater amount of protein content in the body mass composition in prepupae stage BSFL can be considered as high-quality protein source for animal diet, though the substrate composition plays a vital role from the point of view of the variation in EE and ash content level. Another unexplored domain of this study was entertained by Jibin *et al.* [21] who took an effort to find the substitution of natural light sources for BSFL breeding and mating for lab-scale study and reported, mating is possible even without the presence of natural light source with the help of quartz-iodine lamp, which showed a mating rate around 61% of natural illumination. They also tried to find the impact of different light sources on mating phenomenon and stated mating didn't take place when they used rare earth lamp instead of the quartz-iodine lamp. But in case of egg hatching, the study reveals similar duration for both quartz-iodine lamp as well as sunlight treatment (*i.e.* approximately 4 days).

Eventually, the entire research community has been agreed to validate black soldier fly larvae as the most unique and profitable conversion and stabilization agent of the new era with minimal hindrance. The technique is rampant and further research in this domain may help the lower middle-income nations to get read of the unsightly and unscientific dumping yards.

National Status

In a lower and middle-income countries it has been observed, in contrast of other inorganic and inert waste which has a potential value to the rack pickers and recyclers the quantity of generation of organic fraction is predominant (*i.e.* amounting to 65%). But it has been rarely seemed to be forwarded to the treatment facilities or considered as significant source of revenue generation unlike the other part of MSW [22] [23], though in some occasion it may get collected, but its ultimate fate is always in dilemma and either it usually ends up in receiving landfills or on a relatively unscientific open dumping in outskirts of the town, where the material get degraded in the form of large piles under anaerobic environment. Ultimately a feasible treatment has been replenished in the form of BSFL composting, which minimizes the environmental interventions and advances the aspect of public health and sanitation. This novel and economically feasible waste management approach need to be implemented and promoted for overall good [24]. Finally, when it comes to the compost phenomenon, it has been already explored by several researchers all over the globe. On the other hand availability of the relevant literature and information is very meagre in the case of microfauna. And as far as the Indian scenario is concerned, assortment and functionality of this macro-organism was studied in recent past. Ritika *et al.* [25] has tried to establish a correlation between micro and macro fauna and reported that, once the pre-decomposition get completed (15 - 20 days), the partially decomposed material can be supplied to the earthworms namely, *Eisenia-fetida* to examine their interface with the BSFL. But as per the environmental conditions, rearing of BSF should be keenly observed and monitored, because it is rarely hectic in India as larvae thrive better in the tropical environment, hence composting utilizing BSFL should be recommended in India for sustainable waste management [26].

The objective of this review is to emphasize the superiority of BSFL composting over the conventional, time consuming and primitive methods and also to address the existing lagging and drawbacks in this domain and to explore the fraternity with the portrayal of ultimate treatment system, capable of accounting multidimensional aspects such as solid waste and sewage sustainably under a single platform.

2. Biological Waste Decomposition Processes

The process of biological treatment of waste can be explained as the ultimate disposal treatment without generation of any secondary pollutants under controlled environment utilizing biotic organisms. The above treatment category also comprises biochemical and biotechnological treatment systems of advanced and rapid conversion. Though biological treatment systems offer significantly stable end products and require lesser exterior energy inoculation when compared to other conversion processes such as chemical, physical or thermochemical systems, sometimes it may yield extensively slower [27]. An environment with higher moisture content is always preferable to perform any sort of biological conversion, as the conversion agents are living entity. Therefore the waste containing roughly 60% or more of moisture is always recommended to treat under biological stabilization mechanisms. Thus the suitability of biological treatment in order to treat the organic fraction of municipal waste and other domestic wastes in India and other underdeveloped countries is much privileged, where the moisture content of waste often ranges between 60% to 75% [28]. In this context, it's mandatory to mention that during past one-decade black soldier fly larvae composting has emerged as a promising treatment system over other biological processes, because of its rapid conversion speed, sustainability, economic feasibility (*i.e.* due to the production of value-added co-products) etc. But unfortunately as far as the Indian scenario is concerned this treatment system poses pertaining knowledge gap and can be considered as an unexplored domain, which consists significant scope of research and improvement before commercialization [29].

2.1. Composting Mechanism

Composting can be explained as the mechanism of converting the organic wastes under the controlled aerobic environment into comparatively stable end product namely, humus which can be further utilized as manure. Hershey [30] has clearly pointed out that composting has been carried out since the ancient day in order to treat the household waste, though it may not be practiced as per the stringent guidelines and not scaled-up for commercialization but it was evidentially under the practice in Southeast Asia, southern parts of America Greece and Rome. The first scientific documentation and publication regarding composting as a waste treatment mechanism for agricultural and the concept of modern composting has brought into the scenario by Sir Albert Howard and his technical team in 1931. Sir Howard got initial motivation from the farmers of India and China, who use to compost their agricultural waste on regular basis and ultimately use the compost material as fertilizer [31], and thereafter he modified the leggings and drawbacks of the unscientifically practiced Agri based technology and proposed the concept of modern composting, which he named as "Indore Process" [32]. At present, wide ranges of composting mechanisms are available in the market but the fundamental properties are almost invariably in all the techniques. Although various organic materials can be stabilized in the composting process but it's proven to be ineffective against waste with higher oil and fat content. Another vital parameter to be taken into account for composting is moisture content and if all other necessary parameters are satisfied by the waste then it can be readily accepted for further treatment. The most appropriate substrate for composting comprises branches and dry leaves of trees, garden trimming, kitchen waste, crop residue from agriculture, livestock manures, organic fraction of MSW and excreta [33]. Composting can also accommodate miscellaneous municipal waste up to a certain extent, but it's not recommended to feed mixed waste to the pit, especially in underdeveloped countries, where it very often contains hazardous materials, biochemical wastes, heavy metals, plastics and more, which can further cause leachate issues and drastically reduce the quality of compost [14]. Composting process also governed by the local climatic conditions and if the climate is dry then sufficient amount of water needs to be added to the influent during the beginning of the process and also may during the entire conversion period to ensure the optimum workability of conversion agents [34] [35]. These conversion agents can be further classified into two categories namely, micro-organisms and macro organisms and the availability and population density of this of these organisms, subject to temporal and spatial variation [36]. The microorganisms feed into the organic waste by converting them into simple hydrolytes, with the help of enzymes and stabilize the waste by means of removing the nutrient content from it. The energy derived from the substrate gets utilized for binary fission or multiplication, which helps to grow the colony in shorter duration and the feeds voraciously to minimize the treatment period. This microbial activity can be better explained as the fusion of thermophilic aerobic technique, which ultimately yields CO_2 and water. Though the process is somewhat slower but it can be accelerated by controlling the vital process parameters such as C: N ratio, size of the feedstock particle, availability of void space, system of aeration, maintenance of functional temperature, pH, moisture content etc. Even these parameter values largely influence the quality of final compost. Under the diverse conditions, the process kinetics may drastically decrease and even get stunted.

2.1.1. Composting Phases

When the environmental conditions are favorable then the waste received for composting goes through 3 different phases as per the temperature profile of the system which is as follows,

1) Mesophilic phase (continues up to 10 days and the temperature ranges up to 40˚C)
2) Thermophilic or elevated temperature phase (temperature often reaches up to 70˚C, which ensures necessary pathogen removal and it may last form few weeks to couple of months)
3) Maturation phase (temperature gets down and it indicates the inhibition of microbial activity due to possible starvation, which may take a couple of months to finish) [33]. The completion of the composting mechanism is indicated by a potential temperature sink (*i.e.* around 30˚C) and successively followed by the depletion in oxygen level in the voids due to the prevalence of anaerobic microenvironment (*i.e.* due to the death of organisms) [34]. Depending on the rate of waste generation and availability of place composting can be performed at different scales and various technologies can be asserted such as

a) Bin composting with secondary aeration system.
b) Medium scale composting facilitated with routine turning.
c) Large-scale composting facilities, subjected to mechanical aeration and regular turning. The magnitude of the waste is the key parameter which helps to decide the mechanization requirements of the system [37].

2.1.2. Vermicomposting

Introduction:

Vermicomposting is a sluggish degradation and stabilization mechanism which is carried out under the aerobic environment with elevated temperatures through the combined action of micro and macro-organisms. Microbial community first feed on the readily degradable waste and convert it into semi-decomposed matter and makes it ready for further decomposition with the help of earthworms. This decomposed matter prevalently known as "vermicompost" comprises a higher amount of nutrients when compared to ordinary compost [38]. Though the assessment of the significance of earthworms as a potential conversion agent has been claimed by Charles Darwin in ancient days [39], the proper scientific research has been carried out and macro-organisms has been accredited as a renowned catalyst for bioconversion only during the early 80s' [40].

Acceptable input:

A wide range of materials ranging from normal domestic biodegradable waste, sewage, organic fraction of MSW to highly concentrated industrial organic waste almost everything can be supplied as the substrate for earthworms, which it convert and stabilize quite effectively [41] [42]. Despite that earthworm poses some sensitivity and inherent tolerance issues against few substrates such as waste from dairy industries, wastes from livestock farms and wastes with a higher amount of oil content from the restaurants and hotels etc. It is relevant to mention that the particle size of the feedstock has a direct impact and inversely proportional relation with the kinetics of the decomposition mechanism and it can be justified with the phenomenon of increased surface area maximizes the interaction between substrate and conversion agent, therefore resulting in minimization of reaction time.

2.1.3. In-Vessel Composting

It's a kind of composting technique which is generally conducted inside a closed container or vessel under the controlled environment, facilitated with equipment like mixer, homogenizer, aerator, moisture controller etc. [43]. In order to prevent the contamination of waste pile due to oxygen sag and maintain a prevalent uniformity, mixing and turning plays a typical role to ensure optimum efficiency of the process [44]. Another vital factor which decides the suitability of composting as a waste management technique for a certain waste is C: N ratio. Sangamithirai *et al.* [45] recorded a C: N ratio of 30:1 or less is most apposite to ensure optimal conversion. Certain secondary factor which influences composting is air pressure and moisture content. Apparently higher moisture content at the initial phase of the aerobic composting often found to be obligatory to achieve greater temperatures (>80˚C) and sustain it for the longer period. Based on a wide range of studies conducted by several researchers the initial moisture content of 75% associated with an air pressure value of 0.6 bar is highly recommended for optimum digestion of organic waste [46] [47]. If the system is cautiously operated associated environmental risk factors (emission of obnoxious gas, leachate formation etc.) can be almost nullified. But unfortunately, the process often emits volatile gases gasses such as CO_2, CH_4, H_2S, and NH3 etc. which causes greenhouse effect and ultimately leads to global warming. A study undertaken by Cabaraban *et al.* [48] reported an alarming CO_2 emission rate of

0.86 kg/kg of waste from the compost pile, which is adequate to cause a potential threat. Depending on implementation and functionality potential 2.5 lakh tones of organic waste can be stabilized through this treatment system each year.

3. Black Soldier Fly Larvae Composting

3.1. Introduction

Stabilization of biodegradable waste through larval decomposition of *Hermetia illucens* has emerged as a promising treatment during the past decade. The mechanism not only transforms the organic waste but also yields a significant quantity of biodiesel and other value added co-products. Though originated from the Americas, the favourability of climatic conditions and other secondary factors accelerates the distribution of BSF in tropics and subtropics during the successive years and at present, the traces of *Hermetia illucens* can be found in the regions with warm and moist weather conditions throughout the globe [49]. Black soldier fly larvae have been already established as a voracious eater of organic waste and effective conversion and stabilization agent by Dunn [50] while decaying a dead body through larval feeding activity. Bradley [51] also reported the same when the larvae were found feeding on the waste pile in an outhouse in Louisiana. Afterwards, the feasibility of *Hermetia illucens* larvae has been tested against the inhibition of house flies (*Musca domestica*) around the late 50s' and the larvae found to be significantly effective against the breeding of the house flies [52]. They also observed substantive declination in the amount of farm manure when larvae were introduced in massive counts. This influential study acts as a pioneer for the successive scientific researches performed in the domain of waste management through larval feeding captivation of BSF. A diverse range of organic wastes can be introduced to BSFL composting, regardless of its concentration and composition and there is no thumb rule regarding the competence of input material associated with the optimization of key factors. The larvae can be utilized for sustainable waste management with wide range of substrates namely, domestic kitchen and organic municipal solid waste [5] [53] [54] [55], manure from the cattle farm [7] [56] [57] [58], night soil [59] [60], wastes from fishery industries [61], bio-leachate [11] and persistent pollutants [10] etc. Furman *et al.* (1959) has explained the significance of moisture in the influent material over the larval activity and successfully formulated symbiotism between moisture content of the substrate and kinetics of the conversion mechanism. The experimental study conducted by the author for variable moisture level in influent poultry farm waste yields significantly higher volume reduction with subsequent greater moisture content. Although moisture plays a crucial role in bioconversion mechanism, the variation can be accommodated within a certain window (*i.e.* 60% - 80% of total mass) which varies from semi-solid to liquid environment for breeding [62]. In this context, it's quite mandatory to mention that the wastes with higher cellulose content like dry tree leaves, wood etc. are not appropriate to treat with BSFL composting. In the case of commercial utilization of BSFL composting minor pre-treatment is required such as shedding (minimization of particle size), moisturization or demoisturization etc. to meet the supply standards. In order to meet the optimum moisture levels sometimes, it may require dewatering the excess moisture mostly from the green organic waste and faecal matter, or it may also require the addition of water to the excessively dehydrated sources waste such as poultry farm waste. In order to overcome the above drawback, materials with higher and lower moisture content are often mixed together before supplying it to the BSFL composting process. The behavioural characteristics, life cycle period, growth rate of the larvae and biokinetics of volume reduction and minimization, mostly depends on two key factors namely, humidity & temperature. The most favourable temperature for optimum yield and hatching rate was found to be ~30˚C [63] [64]. The life cycle of black soldier fly consists of 6 larval stages and the last instar is alleged pre-pupae. Significant signs can be observed once the larvae transform into pre-pupae such the pale white colour of the larvae becomes blackish and they start moving away from the moisture zone in search of dryness and they also elongate in size up to a certain extent (*i.e.* around 2 - 5 mm elongation). Under affirmative environmental conditions such as 30˚C temperature and 70% Relative humidity of substrate the entire conversion from egg hatching to emerging as an adult use to get accommodated in 30 - 35 days [65]. In optimal conditions larval conversion can efficiently diminish the weight of receiving substrate around 60% - 85% and also capable of converting ~20% of the influent solids which ultimately yields significantly larger quantity of biomass within the period of 15 days [5] [65] [66]. Though BSFL composting can be performed in confined space, there are some operational factors which influence the space requisite like the density of larvae/m^2 of waste, substrate composition, and feeding rate. Inefficient regulation of this parameters often resulting in improportionality between waste reduction and biomass production. Preceding studies claimed optimum conversion often witnessed with minimal larval density [55]. There is a conflict regarding the feeding rate has been observed between the values reported by the authors. Diener *et al.* [67] reported a rate of feeding approximately 1.9 kg/m^2/day while Parra Paz *et al.* [55] encountered much higher figures of 9.8 kg/m^2/day. In order to optimize the conversion efficiency different bioreactor has been fabricated and experimented by several authors [5] [68]. Commercialization of this massive treatment units invariably require fresh biomass of larvae to accommodate enormous quantity of waste hence a productive hatchery is the legitimate secondary unit to make the treatment economically feasible. On the other hand, individual backyard treatment facilities can be handy in order to stabilize the domestic waste; the only constraint in this small-scale application is to maintain the constant count of live population throughout the decomposition period [69]. Therefore this major drawback has to be conquered for individual implementation.

3.2. Overview of Black Soldier Fly and Larvae

Hermetia illucens, customarily known as black soldier fly, categorized under Animilia kingdom and subcategorized as insecta class and diptera order. Though significant identification features are prevalent in adult flies and consistently used in order to segregate it from the common house fly, the larval identification causes significant dilemma among researchers. Despite the criticality of identification during the larval instar, occasionally segregation may carry out based on the size of the larva (**Figure 1**). The detail characteristics and features of BSF are discussed in **Table 1** [70].

Figure 1. Overview of waste decomposition through larval feeding.

Table 1. Identification of distinctive features [70].

Feature	Black soldier fly(BSF)	BSF Larvae	Miscellaneous	Distinguish
Dimensions	*~22.225 mm or 7/8 inch*	27 - 30 mm	Larval width approx 6 mm	BSF larvae from other maggots
stinger or proboscis	Absent	-	Generally present in house fly	BSF from other flies
flying capabilities	Lazy or improper flyer	-	Unlike other variety of flies	BSF from other flies
Wings count	only one pair of wing	-	Wasp contains two pairs	BSF from wasp
Colour of legs	Pale yellow or whitish towards extreme ends	-	Non-Inherent for other flies	BSF from other flies
Colour of abdomen	Reddish and bronze	-	Male poses bronze abdomen while female poses reddish	Male BSF from Female BSF
Subjected to geographical location				

3.3. Body Configuration of *Hermetia illucens* Larvae

3.3.1. Nutritional Profile

The body mass index and the composition of black soldier fly larvae fluctuate extensively subjected to influent substrate quality. Both protein and fat content found to be varying significantly which ranges approximately 35% to 60% and 7% to 40% respectively based on the available quantity of dry matter [71]. Though it's quite evident that the larvae of black soldier fly comprise potentially higher quantity of protein and fat [61] [72], but the configuration of nutritional index relies on numerous factors such as feeding rate, supply quantity, source of substrate etc. [68] [73] [74]. Exemplifying, those larvae feed on swine manure showed elevated protein content compared to those infested on dairy manure [68] [75]. Poultry manure also showed promising potential as a substrate on the larval body composition based on the study undertaken by Oonincx *et al.* [76]. Crude fat content is another prime nutritional element which should be accounted. Though in average a larva comprises ~30% fat of total dry matter, based on the requirement the value can be amplified and chicken manure as a feedstock is capable of addressing this complex phenomenon [56]. Another contradictory study conducted by Nguyen *et al.* [74] reported an enhanced nutritional profile of BSF larvae with higher protein and fat content, those infested on fish and liver rather than poultry manure. Occasionally the body composition of the larvae also varies in the due course of maturation and development. As instance the protein content in larvae varies inversely to its age, assorted studies addressed varying protein percentage for different period of larval development such as ~61% for 5 days old larva (reported as optimum) and subsequent values were 45% and 41% for 15 and 20 days old larvae respectively [77]. Previous studies also quantified the amount of dry matter in young larvae which found to be varying between 20% and 45% of total body weight [67] [78] [74] [76] [79] subjected to factors like stage of larva and influent diet [77]. Unlike the protein content dry matter found to be varying proportionally with the age of larvae and often higher values are encountered in consecutive instars stages.

3.3.2. Mineral Composition

Black soldier fly larvae possess comparatively greater mineral content than other macro-organisms used in waste management [80]. The customary minerals traced with higher concentration in BSF larvae are zinc, manganese, potassium, iron, copper, calcium and phosphorus and other trace elements are copper, sodium, sulphuretc with optimum calcium and phosphorus ratio proclaimed as 8.5 [81] [82]. Though sodium is a vital salt, the level of it found to be quite diminished (*i.e.* ~0.2 g/Kg DM) comparing to earthworms or other macro conversion agents [80] [82] [83]. Predominantly mineral content found to be varying with discrete feedstock and poultry manure invariably yields greater crude mineral content when compared to other substrates [84]. Exemplifying, phosphorus content found to be essentially greater when the BSF larvae reared on chicken feed. Nutritional profile of BSFL shows a comparatively higher percentage of ash content which often reaches around 25% of total dry matter [78] [81]. Consistently most of the authors reported greater values calcium and ash content in body composition of BSFL, which can be moderately justified by the phenomenon of calcium carbonate secretion from the epidermis of BSF larvae [85]. Contrarily, the calcium content for a freshly emerged adult is very scanty which ranges around 0.035% of total DM as most of the body calcium of larvae use to get utilized for exoskeleton formation during pupal conversion [78].

3.4. Adaptability as Animal Diet

In this section, brief details of the preceding studies will be discussed those investigated the feasibility of BSF larvae as alternative protein-rich animal diet.

BSF as Swine and Chicken Feed

Black soldier fly larvae found to be nutritional and worthy as swine feed and vice-versa, because of containing the higher amount of crude protein, Ca and also for being palatable. Those larvae infested on the pig and poultry manure convincingly showed higher palatability. Seldom certain essential amino acids such as cystine, methionine etc. need to be supplemented in the normal diet to overcome the comparative inadequacy of protein [81] [86]. However, a blend of proteinaceous constituents and BSF larvae often served together to conquer the impacts of a higher quantity of fat and ash content on the feeder [85]. However, the digestibility of different feedstock tends to be varying for swine as well as broiler chickens. Those pigs and hens fed soybean diet rather than larval diet accounted for better growth accomplishment and exhibits greater quantity of nitrogen and DM successively 77.3 and 85.1 (soymeal) v. 76.1% and 77.2% (BSF meal). Additionally, larval diet found to be quite ineffective in the case of weaned swine and the production efficiency doesn't show any affirmative sign, hence further sorting and removal or cleansing of contaminated larvae often recommended prior to supply [83] [84] [86] [87] [88]. Contradictorily partial replacement (*i.e.* ~50%) of soymeal with defatted larvae resulted significantly well as broiler feed and also uplifts the rate of egg laying, and body growth [89]. Scientific studies revealed consumption of larval diet yield probably greater metabolic energy and higher quantity of amino acid from the co-digestion which makes it a worthwhile as splendid poultry meal [87] [90]. Furthermore, National Research Council [91] and Arango Gutierrez [83] claimed the feasibility of larvae as a poultry feedstock with all essential mineral contents to accelerate the growth factor of chicken.

3.5. Characteristics of Feedstock

Apart from the biological factors, there are certain physical factors which can influence the performance of this conversion agent. For instance, the thickness of the substrate layer (e.g. raw meat) often affects the larval development period and survival negatively [73] [74] [92]. Since later 80s' numerous studies reported that the optimum moisture content of 60% to 70% is adequate for the survival of

BSF larvae and more likely it grows on concentrated and homogeneous waste [93]. Anyhow, the implementation of BSFL composting as a pilot-scale waste management facility needs to overcome certain reasonable hurdles such as non-uniform and non-homogeneous influent waste characteristics, variation in moisture level of the substrate, evaporation losses, influence of other rodents etc. It has been reported by numerous author that BSF larvae somehow survive in extremely wet conditions with moisture content ranges greater than 90%, but the lowering of conversion efficiencies often noticed in this cases [94].

3.6. Larval Density

Larval concentration per square meter of waste is another key factor which influences the decay rates [95] [96] [97], but the inadequacy of relevant literature makes this issue catastrophic in order to determine the most pertinent density. Anyway, assorted studies performed in this domain tries to address the above issue with a rational approach by the inclusion of several parameters such as thickness of substrate layer (1 to 2 cm), size of the bioreactor etc. The most recommended concentration of larvae for optimal composting efficiency is approximately 1.5 larvae/cm^2 of waste [7] [63] [67] [73] [74] [76] [98]. The design density also varies occasionally with the influent feedstock. A greater concentration of larvae (*i.e.* ~2.5 larvae/cm^2) reported being apposite in the case of poultry manure being the influent material in order to achieve higher growth rate [98]. Banks *et al.* [59] reported a maturation period of 30 days if the larvae allowed infesting on human excreta with varying concentrations of 0.023, 0.21, and 0.32 larva/cm^2 of waste surface area respectively. But it is quite evident that greater larval accumulation often gives negative influences and the utmost larval weight recorded till date is accounted with a meagre density value of 0.32 g of faecal matter per larva [99]. The susceptibility of BSF larvae often depends on the environmental conditions of the study area, biological and physical factors, origin of the substrate etc. Hence utilization of locally available species with higher compatibility with the certain feedstock shows promising results and always recommended [100].

4. Waste Derived Products and Utilization

The elementary end-products originated from BSFL composting are the live biomass population and the mature compost or humus. The larvae can be further utilized as the protein supplement for poultry livestock and aquatic fishes instead of ordinary diet after performing the de-fatting operation which potentially amplifies amino acid content in larvae. Several studies have been conducted by different researchers on this aspect and the BSF larvae were found to be admissible as an alternative to inferior traditional diet for poultry and swine farms [81] [101]. Other distinct application includes synthesis of value-added co-products such as Biodiesel, grease, and sugar [16]. Ultimately the residue which contains stabilized nutrients such as nitrogen; phosphorus etc. can be utilized as a soil conditioner. Nevertheless, because of the shorter stabilization period, the compost needs to be processed through a maturation treatment to inhibit the anaerobic growth and successive oxygen deficiency; otherwise, it may suppress the germination of seeds and abolish photosynthesis [102]. Despite its entire expedience, the process may encompass few minor drawbacks such as pathogens contamination in the food chain and infiltration of persistent pollutants into livestock etc. Tests had been carried out by several researchers to understand the interaction between the BSF larvae and different pathogens and it was reported, though BSF larvae can potentially reduce the activities of Salmonella spp. but quite ineffective against other spore-forming pathogens namely, Bacteriophage, Enterococcus spp. and also eggs of helminth [60]. Moreover, a bioaccumulation problem could be encountered when contaminated waste directly supplied to the composting yard without any sort of pre-treatment or precautionary screening [10]. Fascinatingly, BSFL composting degrades hazardous substances from pesticide and pharmaceutical industries at a much faster rate. Different substances had been investigated by Lalander *et al.* [8] in order to analyze its feasibility with the decomposition process and a shorter half-life has been observed in all the trials with no trace of larval bioaccumulation. So far the published articles in this domain predominantly focused on the mechanisms like rate of conversion, mating deportment, rate of survival against different exposure conditions, customarily experimented at lab scale. Eventually, a significant scope of sustainable waste management is attributed by means of BSFL composting especially for lower middle-income nations. Incredibly the climatic conditions of these nations are found to be most favourable for the breeding and survival of black soldier fly and its larvae. Adequacy of influent water plays quite a vital role in this regard and an integrated model that incorporates sewage and solid waste treatment into a single platform would be promising [103]. Contemporary research in this domain expected to fill the pertaining knowledge gap and formulate a baseline data which can be utilized as a benchmark by future researchers. Based on the recent finding by certain researchers establishment of symbiotism between the microorganisms and BSF larvae has been claimed and its impact on the behavioural characteristics, life cycle attribute, feeding, and conversion rate are yet to analyze [72] [104]. Apart from utilizing the full-grown BSF larvae as animal diet [8] [10] [60] [66] [87], a typical research is required in order to commercialize BSFL composting on a pilot scale which may be possible with the collaboration between academic and industrial entities.

5. Conventional Composting Vs. BSFL Composting

Though conventional composting is in practice since the early twentieth century, BSFL composting has emerged as a promising alternative since last few decades. This composting technique is capable of addressing multisource organic waste through larval infestation of *Hermetia illucens*, unlike the conventional composting process where earthworms (earthworms are subjected to extinction) and microorganisms are utilized as conversion agent. Numerous preceding studies precisely indicated the significant difference between the traditional composting and this novel technique tabulated in **Table 2**. Over the years, due to the enormous advantages BSFL technique over the ordinary composting it surpasses the time-consuming and laborious conventional process and it's still rampant. The plethora of this innovative technique can be traced in the nations of south-east Asia, predominantly China [105] [106].

6. Portrayal of the Reactor

The fabrication of Integral Larval Grub Composting Reactor (ILGCR) is undoubtedly one of the most delicate issues which has explicit influence the efficiency and success of entire treatment facility and requires utmost attention. Decentralized approach incorporated with suitable pre-treatment techniques (e.g. screening, homogenizing etc.) found to be effective for a wide range of substrate intake [107]. Present reactor modules are capable of addressing a wide range of waste coming from the variety of sources, but a pertaining knowledge in this area requires extensive research. The preliminary constrain in this domain is the selection of apposite feedstock for larvae and vice-versa, which is regulated as per European legislation for BSF. On other hand biosafety also plays a significant role in environmental intervention and release of any sort of pathogen or toxic materials is highly unappreciated [103]. Ultimately a complete and wholesome treatment facility is obligatory to meet the goal of sustainability and integrated waste management [108]. Thus, a treatment unit capable of addressing wastewater and solid waste under a single platform is proposed and the schematic has been portrayed in **Figure 2**. The proposed reactor will also encompass

Table 2. Comparison between ordinary and BSFL composing [30]-[35] [105] [106].

Phenomenon	Ordinary Composting	BSFL Composting
Duration	*4 - 5 weeks*	12 - 15 days
Conversion agent	Earth worms & microorganisms	Black Soldier Fly Larvae
Optimal temperature	60˚C - 75˚C	~30˚C
Optimal moisture	40% - 60%	60% - 75%
Applicable feedstock	Except persistent pollutants	All most everything
End product	Compost or manure	Humus, biodiesel, protein, grease, sugar
State of end product	More stabilized	Occasionally requires maturation treatment
Gas emission	Anaerobic conditions often emit green house gases	Completely aerobic process and nil emission
Additional benefit	Nil	Suppress the growth of *Musca Domestica*
Values are subjected to environmental conditions		

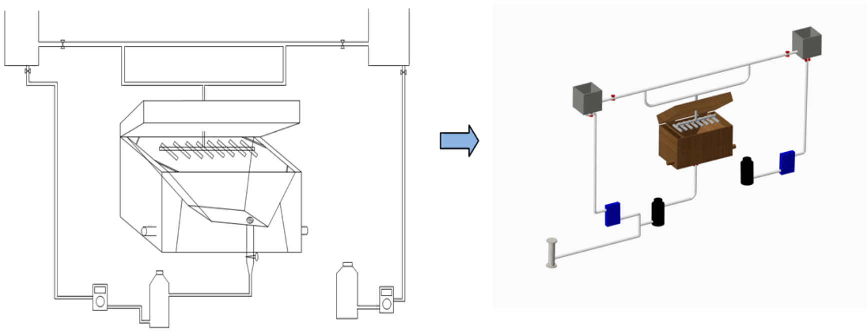

Figure 2. Schematics of the proposed reactor (rendered view).

bioleachate treatment, which will be further processed into natural gas and biogas for revenue generation [109]. In other words, the commercialization of the bioreactor may create a revolution in integrated waste management facilities and open new economic niche for small-scale entrepreneurship.

The reactor consists of two major working elements namely, waste conversion/maturation element and liquid circulation and recirculation unit. Rest of the subordinate units is there to support the fundamental working procedure. **Figure 3** shows the overview of the bioreactor. It comprises two upper-head tanks with the flow regulators, a sprayer, a grub composting area, pupal segregation and removal bucket, leachate drain with stopper, and a leachate collection tank with a recirculation system. Two peristaltic pumps are required in order to run the operation in continuous mode.

7. Working Mechanism of ILGCR

Initially, the waste needs to get introduced into the active composting zone, where larvae will be working upon it and decompose the waste. Near to the top opening four hinges has been provided to captivate the entry of larvae in unwanted zones and regulates the larval movement only towards the pupal segregation bucket. A leachate drain has been provided with a regulation system to drain the percolated wastewater from the system. A slope of 20˚ has been provided with the horizontal towards the drain opening. Pupal segregation bucket segregates the pre-pupae from the juvenile larvae and it comprises an exit hole to take out the same. A fall down slot of 1.5-inch length has to be given on both of the corners of the reactor. The upper-head tank placed in the top left corner of the reactor is meant for bio-leachate supply, which has a flow regulator in order to control the inflow volume. The other upper-head tank placed on the top right-hand side of the reactor is meant for sewage supply. The similar kind of flow regulating provision has been given to it. The moisture supplied from the upper-head tanks finally reach the sprayer and get uniformly distributed over the solid sample. A bio-leachate collection tank with influent flow regulator is placed near the bottom of the reactor. The inflow regulator only opened once in three days, once the leachate gets thickened. At the junction of the reactor and the leachate drain pipe, a fine mesh needs to be used to arrest the entry of larvae

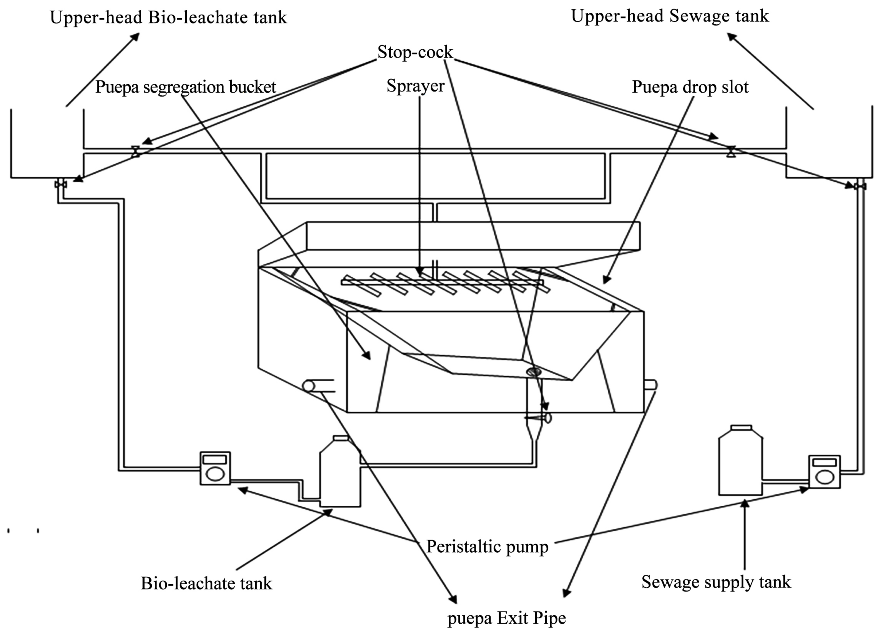

Figure 3. Indexed bioreactor schematic.

into the drain pipe. Two nos. of the peristaltic pump has been are required to the system to convey the bio-leachate and sewage from the bottom tanks to the upper-head tanks.

8. Conclusion

During the past decades, plenty of biological treatment methods have been practiced in order to achieve the optimum bioconversion and stabilization associated with maximum valorization by means of synthesizing value added co-products, which can further make the technology economically feasible. Though all the technologies were capable of converting the bio-waste quite effectively, in most of the methods, the ultimate goal of sustainability has found to be under considerable threat. The feasibility of black soldier fly larvae as a conversion agent for various organic wastes has been emphasized in this review. The aim of this review is to establish the superiority of BSFL composting over other existing techniques based on a comparative analysis method. The review also encompasses a detailed discussion on the benefits and drawbacks of the BSF technique based on numerous preceding studies, which highlights the expediency of the mechanism as per the present market requirement. Although, the ultimate success of the project significantly relies on some certain factors such as availability of fund, maintenance and operational cost, source segregation (*i.e.* for MSW), waste characteristics, and waste generation rate etc. which further influences the end product quality [110]. The principal selection criteria of a certain technique also include the valorization of the end-products, depending on its requirement and market value. In this context BSFL composting surpass the existing and conventional techniques by a considerable margin. Hereof, a possible collaboration between the local body and private non-profit organizations may lead to the commercial success of BSFL composting, though the assessment of local condition is quite mandatory. Although the concept of "waste is a misplaced resource" has been established among the literate people, but still, a greater fraction of the society has a psychological barrier to endorse the waste-derived products as a substitution to the similar virgin goods [111]. Zhang *et al.* [112] worked on the aspect of implementation in China and concluded that the development of market and technology transfer can make this technique dominant over the other methods. At the end, more sophisticated and holistic approach towards waste treatment renovated with technology up-gradation is obligatory for lower middle-income nations.

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