ABSTRACT

In low- and middle-income countries like Pakistan, 50-75% of municipal solid waste (MSW) comprises of organic waste (biowaste) whose management and treatment are one of the most challenging tasks for the waste management authorities. Most of the local authorities in these countries are eager for the projects related to the recyclables' management due to their economic value. Organic waste receives less attention for perceived lower economic value. Waste treatment using Black Soldier Fly Larvae (BSFL) scientifically known as *Hermetia illucens*; (Diptera: Stratiomyidae) is a promising sustainable solution for recycling organic waste component. This study assessed and compared the satellite (at the source: household level) and centralized (at field near the source) organic waste treatment approaches using BSFL technology.

A pilot scale research study was conducted to evaluate rearing performance of Black Soldier Fly (BSF) for the first time in Pakistan under local conditions of a semi-arid region with minimum investment and resource utilization. BSF rearing and waste treatment experiments were performed at Pakistan's first BSFL organic waste treatment facility established jointly with The Urban Unit in Sahiwal. Parameters such as BSF emergence rate, number of eggs per female fly, BSFL hatching rate and developmental duration of each life stage determined the rearing performance and suitability of BSF life cycle under natural environmental conditions. A total of 13 BSF life cycles were studied that included following developmental and adult stages to complete one life cycle: i) pupation ii) flies emergence iii) adult mating, copulation and egg laying iv) egg hatching v) larval feeding stage and vi) transformation to prepupae. Temperature and relative humidity for each stage was also recorded in order to evaluate the performance under fluctuating weather conditions. In this study mean BSF emergence rate and BSFL hatching rate of 58.8% (SD 15.2) and 44.5% (SD 21.8) were achieved respectively. The number of emerged flies and number of prepupae in dark cages; and number of hatched larvae and number of eggs showed a significant positive correlation $R = 0.75$ (11) and 0.92 (11) $p<0.05$ respectively. On average BSF took 49.5 days (SD 3.20) to complete its one life cycle under ambient temperature and RH ranging between (22-35°C) and (24.7-89.3%) respectively. The mean developmental duration of fly emergence, pre-oviposition, egg hatching, larval feeding,

temperature and RH ranging between (22-35°C) and (24.7-89.3%) respectively. The mean developmental duration of fly emergence, pre-oviposition, egg hatching, larval feeding, prepupae metamorphism developmental time of pupae to fly emergence was found to be 15.6 days (SD 1.6), 3.5 days (SD 0.5), 3 days (SD 0.6), 27 days (5 days chicken feed; 22 days waste feeding; SD 2.5), 3.8 days (SD 1.2) respectively. The study conducted in Pakistan resulted in lower average BSF emergence, BSFL hatching rates and number of eggs/female fly (48/fly) with a longer life cycle duration as compared to those obtained at FORWARD BSF site in Indonesia. In Pakistan, BSF took longer time to complete its life cycle as compared to 44 days in Indonesia. Controlled environmental conditions can improve BSF rearing performance in Pakistan as being done in the facility in Indonesia. BSF tolerated the local conditions of Pakistan and successfully completed all life cycles without need to maintain controlled environmental conditions.

In low- and middle-income countries waste management services tend to be costly and inefficient with household biowaste as one of the major contributors of municipal solid waste. Organic waste recycling using BSFL at small decentralized points i.e., "satellite level" can reduce burden on waste collection and transport services, divert waste from dumping sites and add economic value to a yet underutilized resource. The heterogeneous composition and high nutritional value of household biowaste makes it a preferred substrate for treatment by BSFL. This study evaluated the practicability of BSFL bin use at household level to handle kitchen biowaste by placing three bins per house each after 15 days interval of larval feeding. It was found that 50% of the household contacted cooperated well to continue the experiment. The reasons for agreement and disagreement were documented on the basis of open discussion with households. Operational aspects and set of instructions for BSFL bin handling were documented based on these first findings and shared with all households that agreed to continue for the remaining period of the study. During the study duration key parameters to evaluate waste treatment performance and larval development were determined which included waste dry matter weight reduction, volumetric reduction, final prepupal weight, biomass conversion rate (BCR), metabolism and proportion of residue left after treatment. For more accurate quantification of larval activity, BSFL approximate digestibility (AD) and conversion efficiencies of ingested (ECI) and digested waste (ECD) were also calculated. BSFL biowaste bin

treatment at household level resulted in 89.6% (SD 6.77) mean waste dry weight reduction and 81.3% (SD 4.8) mean waste volumetric reduction. Response surface analysis showed that initial moisture content of waste was more significant for achieving greater waste dry weight reduction than the feeding rate. The average adult larval dry weight of 69 mg/BSFL (SD 7.1) with a bioconversion rate of 12.9% (SD 1.7) and 77.3% (SD 6.0) metabolized waste was achieved. A very small proportion of 10.4% (SD 6.8) remained in bins as a residue. On average 87.7% (SD 9.1) of household kitchen waste was actually digested (AD) by BSFL, whereas 16.6% (SD 2.2) was efficiently converted into biomass. Source separation for organic waste at the source with mutual understanding and cooperation between households and waste management authorities are factors to successfully implement the idea of BSFL assisted biowaste bins.

BSFL operational guidelines issued by EAWAG Switzerland and most of the previous studies recommended 5-10 cm thick waste layers (maximum 23 cm) for the treatment process that may need large space especially for treating huge quantities of waste. This study explored performance of BSFL waste treatment process for waste feeding layers with thickness between 10-100 cm on a pilot scale in Pakistan at a Centralized Waste Treatment Facility. Waste layer thickness and 50% thickness reduction with time, dry matter waste weight reduction and volume reduction which indicated degree of waste treatment were the key parameters studied during the process. Furthermore, larval weight gain, bio conversion rate (BCR), residue and metabolism were also calculated. Waste layer thickness reduction varied between 68.9 (SD 0.75) and 96.7 % (SD 0.65), waste dry weight reduction 45.2 (SD 5.20) – 96.5% (SD 0.20) and volume reduction was found to be between 64.0 (SD 3.46) and 87.9% (SD 2.61) for layers with thickness of 10 – 100cm. Final larval weight and bioconversion rate ranged between 0.031 – 0.047 g and 6.01% and 9.94% respectively in different layers. Metabolized waste was more than the residue in all samples except the one with 90cm waste layer thickness. This study confirmed that space foot print of BSFL treatment process can be decreased using waste layers with higher thickness than the widely practiced 10 cm thickness.

It was also observed that 50% thickness reduction occurred in first 3-9 days in most of the samples. This study confirmed that BSFL treatment is a promising option to treat organic waste.

In low- and middle-income countries like Pakistan there are huge costs involved in municipal solid waste management and lack of financial resources by local authorities worsen the situation. Higher density and lower compressibility of organic waste requires more space and higher transportation costs. Any solution to handle organic waste component at or near the source of generation may help authorities to tackle the waste management problem cost effectively. This study compared the costs of treating organic waste at source (satellite) and near the source (centralized) with the cost of conventional waste management system. The costs of primary, secondary and tertiary waste collection and transport along with the safe disposal have been compared with establishing and operating cost of the two BSFL assisted organic waste treatment systems. The cost of conventional waste management system was found to be Rs. 4,194/ton. This included capital and operational costs of different segments i.e., primary collection, secondary collection & transport, tertiary transport, safe disposal, leachate treatment, closure and rehabilitation of the disposal site. It was found that satellite system eliminates the need of all above mentioned segments thus resulting in huge savings of up to 76% as its cost was calculated to be merely Rs. 989/ton. This cost included cost of bins, their maintenance, tools, training for bin handling, BSFL production and logistics for supply of BSFL. In case of BSFL assisted centralized organic waste treatment facility the conceptual and structural designs were prepared leading to extraction of Bill of Quantities. The capital cost required for infrastructure and equipment was then calculated. Similarly, operational cost was calculated included human resource, consumables, utilities and other relevant expenses. It was found that cost of treating one ton of organic waste at such a facility would be Rs. 3,063/ton. When compared with conventional system, the cost of primary collection would be same and cost of secondary collection & transport would be half considering the facility is located at half of the distance as compared to disposal site of conventional system. The system may lead to savings of up to 27% as compared to the conventional system. In both cases the BSFL assisted systems would help to reduce costs of waste management systems as well as improve environment by reducing transport related emissions and land use at the final disposal sites.

The quality of end product from both the waste treatment approaches was tested for its decomposition by determining the changes in pH, volatile solids VS (organic matter) and C/N ratio before and after 15 days of BSFL waste treatment. In both cases larvae were added once at the start of experiment according to the amount of waste. Fresh waste and residue quality of household kitchen waste and fruit vegetable waste from satellite and centralized waste treatment approaches was tested. The results showed that BSFL treatment increased the pH of household kitchen waste from slightly acidic (pH 5.2) to slightly alkaline (pH 7.5) and acidic (pH 4.2) to slightly acidic-neutral (pH 6.8) in fruit and vegetable waste. However, it reduced the VS content and TOC in the residue of household kitchen waste and fruit vegetable waste from 88.7% (SD 1.4) to 69.8% (SD 1.6), and 48.8% (SD 1.6) to 38.8% (SD 2.5); 92.5% (SD 1.1) to 84.6% (SD 2.4) and 51.4% (SD 0.9) to 47.0% (SD 0.6) respectively. The C/N ratio decreased from 19.8 (SD 0.8) to 15.3 (SD 3.0) in household kitchen waste residue and increased from 27.2 (SD 2.0) to 28.8 (SD 4.0) in fruit and vegetable waste residue. The TN content increased in kitchen waste residue from 2.49% SD (0.1) to 2.60% (SD 0.3), and decreased from 1.95% (SD 0.1) to 1.63% (SD 0.2) in fruit vegetable waste residue after BSFL treatment. Fruit and vegetable fresh waste and its residue was more acidic with higher VS and TOC content and lower TN content as compared to kitchen waste. Values of quality parameters for household kitchen waste residue were within the preferred limits of a mature compost except C/N value of fruit vegetable waste residue. Therefore, the residue produced after BSFL treatment of household kitchen waste is considered more suitable for soil application.

As a result of the study, it can be stated that BSF may be reared in semi-arid region of Pakistan to be used for successful organic waste treatment. The treatment can be done at satellite (source) or at a centralized facility resulting in huge costs saving. The BSFL assisted waste treatment may help authorities in the developing countries to tackle problem of organic waste management.