USING BLACK SOLDIER FLY LARVAE TO MAKE COMPOSTING MORE EFFICIENT AND PROFITABLE

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Table of Abbreviations

BSFL	Black Soldier Fly Larvae
BD	Bulk Density
ft	Foot/Feet
g	Gram
Gal	Gal
in	Inch/Inches
kg	Kilogram
lb	Pound
OM	Organic Matter

Abstract

As climate change continues and resource management becomes crucial for sustainability, food waste and OM should be treated as resources. OM anaerobically digests when buried underground producing methane, it increases the weight of transported trash, and is taking up unnecessary space in landfills (Shelomi, 2020). Composting is the bioconversion of OM into a usable and valuable soil amendment (Makan & Fadili, 2020). Due to downsides of traditional composting, the process on a small- and large-scale disincentivize the practice. However, cultivating BSFL in compost incentivizes the diversion of food waste and OM from landfills to be converted into larvae. BSFL, which consume about 200 mg per day, feed on OM, usually decaying organisms, food waste and manure (Attiogbe et al., 2019). Using BSFL in composting has benefits of decreasing the BD of food waste inputs quickly, reducing the processing timeline, requiring less space, and producing profitable larvae. BSFL composting becomes a closed loop system where OM is produced and fed to BSFL, and then the larvae can in turn be used as livestock feed (Shelomi, M., 2020). By exploring the inputs and outputs of traditional and BSFL composting systems, conclusions on the benefits of BSFL composting are made showcasing the efficiency, productivity, and profitability of BSFL composting. Over the timeline of traditional composting, the BSFL composting process even scaled up to handle the same amount of waste could have been completed eight times with at least five times less labor put in. By dividing the value of the composting outputs by the hours of labor, BSFL showed to be $5 more profitable per hour. Even though the cubic inches per g of OM handled were greater with the BSFL bin this excluded the facts that BSFL were immediately converting waste and always required the same amount of space. On the other hand, traditional composting, also a collection of waste, needed extra space to turn the compost pile effectively.

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Introduction

BSFL are crucial to decomposition and live in subtropical and temperate regions. The larvae, which consume about 200 mg per day, feed on organic matter (OM), usually decaying organisms, food waste and manure (Attiogbe et al., 2019). Their ability to consume 15 times their own weight in one week and be safe insects to work with, makes them ideal for composting, zero waste applications and farmers (Shelomi, 2020). Due to organic waste decomposing anaerobically in landfills, greenhouse gases such as methane are being produced and released by landfills. To combat greenhouse gas production and practice resource management diverting OM from the landfill and using compost as a treatment system is important (Gershuny & Martin, 2018). On-site composting is incentivized by the water weight in food waste decreasing gas mileage and increasing fees when transporting trash (Shelomi, 2020). Food waste could be composted on site and used as a soil amendment instead of being buried in a harmful environment for decomposition. The downsides to composting disincentivize municipal composting systems which include transportation costs, long timelines, ample space, and low payback ability (Shelomi, 2020). However, with BSFL the BD of food waste inputs is decreased quickly, the processing timeline is greatly reduced, less space is required, and profitable larvae are produced. BSFL composting becomes a closed loop system where OM is produced and fed to BSFL, and then the larvae can be used as livestock feed (Shelomi, 2020). By exploring the inputs and outputs of these composting systems, conclusions on the benefits of BSFL composting are made showcasing the efficiency, productivity, and profitability of BSFL composting.

Literature Review

Food Waste

Approximately 81.4 billion lb or 36.9 billion kg of food are wasted every year in the U.S. according to the EPA (2016). With a population of 323.1 million people in the U.S. in 2016 that is approximately 0.690 lb or 0.313 kg of food wasted per person per day as shown in equations 1 and 2.

$$\frac{81{,}400{,}000{,}000\ lbs/yr}{323{,}100{,}000\ people} = 252\frac{lbs}{person} = 114\frac{kg}{person} \tag{1}$$

$$\frac{252\ lbs}{365\ days} = 0.690\frac{lbs}{day} = 0.313\frac{kg}{day} \tag{2}$$

Traditional Composting

In this context traditional composting refers to composting without the intentional addition or cultivation of worms or larvae. Composting converts OM into a soil-like substance that is uniform in structure, which can be used as organic fertilizer or to remediate infertile and depleted land (Weppen, 2001). Composting comes in a range of systems from active, frequently turned or mechanically processed, to stagnant, turned once a month to a few times a year (Gershuny & Martin, 2018). Composting can be done with one heap of OM that has organic waste continuously added to it. Or, it is best done in batches, where OM is added one time and handled correctly for the rest of its decomposition bioprocess (Weppen, 2001). A deliberate process, composting consists of combining OM with correct levels of carbon, nitrogen, oxygen, moisture, and temperature, to have microorganisms efficiently break it down into finished compost or soil (Gershuny & Martin, 2018). When done in batches, the compost is more likely to experience the necessary high temperatures related to microbial, biochemical activity and will become finished compost quicker than continuous compost systems (Weppen, 2001).

Home Composting

There are a variety of methods for home composting which can affect the rate of decomposition, amount of labor, and greenhouse gas emissions. The correct amount of oxygen, critical mass, carbon to nitrogen, and moisture is required to attain optimum hot composting temperatures of around 60°C (Gershuny & Martin, 2018). Hot composting requires more labor and an initial batch of compost while cold composting requires less labor but much more time and can have the continuous addition of compost (Gershuny & Martin, 2018). A 10-foot chicken wire fence with four wooden stakes creates a cylinder about three ft in diameter and five ft in height. Since this bin is without forced aeration or mechanical processing, it is a stagnant pile. For a stagnant pile to become finished compost there is less labor but more time required, while unwanted anaerobic digestion occurs as well (Gershuny & Martin, 2018). Turning a stagnant pile will compost the OM correctly and aerobically but will add to labor hours (Gershuny & Martin, 2018). For comparison, an average household composting bin, which consists of mostly wet, nitrogen-based food waste and dry carbon-based materials, filled to 16 cubic feet is approximately 400 lb or 181 kg. This is according to the EPA's 2016 volume-to-weight conversion calculator which lists 1 cubic foot of food waste to weigh approximately 25 lb and is shown in equations 3 and 4.

Compost Bin Size Calculation

$$4\ ft * 4\ ft * 4\ ft = 16\ cubic\ ft \tag{3}$$

Compost Bin Weight Calculation

$$16\ cubic\ ft * \frac{25\ lb}{1\ cubic\ ft} = 400\ lb * \frac{1\ kg}{2.20\ lb} = 181\ kg \qquad (4)$$

Shown in equation 2, one person produces, on average, 0.690 lb of food waste per day. To fill up a typical compost bin for a four-person household it can take up to 145 days or 5 months (equations 5 and 6).

$$4\ people * \frac{0.690 \frac{lb}{person}}{1\ day} = 2.76 \frac{lb}{day} \qquad (5)$$

$$\frac{400\ lb}{2.76 \frac{lb}{day}} = 145\ days \qquad (6)$$

Without adding to this pile, aerating, or turning it at least every month, or keeping it above freezing temperatures, the pile can become inactive or anaerobic (Gershuny & Martin, 2018). Reaching temperatures of at least 130˚F to preferably 160˚F or higher is crucial in producing finished compost (Gershuny & Martin, 2018). After 6 months the amount will decrease to approximately 40% in BD resulting in 240 lb or 109 kg shown in equation 7 (Breitenbeck & Schellinger, 2013).

Approximated Finished Compost Weight

$$400\ lbs * (100\% - 40\%) = 240 lbs * \frac{1\ kg}{2.20\ lb} = 109\ kg \qquad (7)$$

The finished compost can be used as soil in a garden bed. Forty lb of soil cost about $5 so, this compost can replace $30 worth of soil as shown in equation 8 (Lowes, 2021). The true value of compost can be $50 per 40-pound bag making the true value of this finished compost about $300 as shown in equation 9 (Lowes, 2021). If using the higher value, a homeowner could make a profit of $1.67 per day with a timeline of six months as shown in equation 10. This does not include the time it takes to fill up the 16 cubic foot bin. Unless doing large scale composting, this does not create incentive to recycle food waste. Selling compost to farmers is difficult due to their desire to cut costs for larger profits (Shelomi, 2020). Traditional composting at home is most ideal for gardeners.

Cost of Soil

$$\frac{240\ lbs}{40\frac{lbs}{bag}} = 6\ bags * \$5 = \$30 \tag{8}$$

Cost of Compost

$$6\ bags\ * \frac{\$50}{bag} = \$300 \tag{9}$$

Compost Profitability

$$\frac{\$300}{180\ days} = \frac{\$1.67}{day} \tag{10}$$

Large-Scale Composting

A necessary recycling system, large-scale composting is slowly growing throughout the world (Shelomi, 2020). Most facilities execute the windrow system creating long and high piles of OM or compost that is turned using a windrow machine (Makan & Fadili, 2020). The production of finished composting requires time, energy, space, and money to operate efficiently (Gershuny & Martin, 2018). The finished product is of high quality, but a much lower BD compared to initial food waste and OM inputs (Breitenbeck & Schellinger, 2013). Traditional composting is more profitable at a larger scale which incentivizes the collection of food waste as a valuable resource input for this process (EPA, 2016). Composting is a sustainable solution for an organic waste management system, however the mechanisms required for efficient composting can have high energy demands causing questionability over the sustainability of composting (Makan & Fadili, 2020). Historically composting was very important on farms, to handle and reuse manure. However, with monoculture farms there is a lack of manure on most present-day, large farms (Gershuny & Martin, 2018). Moreover, incentive for farmers to invest time and money into these practices has decreased due to the focus on short-term profits which neglects the land and integrative farming practices (Gershuny & Martin, 2018).

BSFL Composting

Even though temperature and other factors are still at play, the use of BSFL in composting decreases the time, labor, and space needed compared to traditional composting. One BSFL can consume an average of 200 mg of food waste per day over two weeks (Attiogbe et al., 2019). BSF prepupae, or larvae, are also acceptable replacements for animal feed, specifically fish meal or poultry nutrition (Guo et al., 2021). Once BSFL are added to food waste or vice versa, all there is left to do is wait until they are ready for pupation in which they will self-harvest and be ready for use, usually as animal feed (Diclaro & Kaufman, 2009). BSFL can be reared in a closed habitat or through continuous culture. A closed habitat usually takes the form of a closed container with eggs placed within it one time without allowing any new flies, eggs, or larvae to be added to the container or food waste. Continuous culture is usually in a large enclosure that allows the flies to complete all stages of life. For example, a system of continuous culture could be used within a livestock enclosure where BSFL could provide a constant waste management system with ongoing larvae inoculation, breeding, and consumption of manure (Sheppard et al., 2002).

Home BSFL Composting

For a four-person household, 2.76 lb of food can be thrown away per day. Over the two-week period that a BSFL system is consuming there could be approximately 39 lb or 17.53 kg of food waste produced by a household as shown in equation 11. This is enough to feed 6,261 BSFL as shown in equation 12 and 13. Since an adult female BSF lays 500 eggs near decaying matter, the eggs from approximately 12 female BSF would be required to handle food waste every two weeks (Diclaro & Kaufman, 2009).

$$2.76\frac{lb}{day} * 14\ days = 38.64\ lb * \frac{1\ kg}{2.20\ lb} = 17.53\ kg \quad (11)$$

$$200\ mg * 14\ days = 2800\ mg * \frac{0.000001\ kg}{1\ mg} = 0.0028\ kg \quad (12)$$

$$\frac{17.53\ kg}{0.0028\frac{kg}{larvae}} = 6{,}261\ larvae \quad (13)$$

Sheppard et al. (2002) had 5,000 larvae in a 56 by 40 by 13 cm or 22 by 16 by 5 in pan and fed them an approximate total of 10 kg of food waste over their larvae stage in a closed composting system. That is approximately 200 mg or 0.2 g of food waste per larvae per day as reported by Attiogbe et al. (2019) as well. The 29,120 cubic centimeters or 1,777 cubic inches is about 1 cubic foot as seen in equation 14 and is the amount of space required for the 5,000 larvae. Equation 15 shows that about 5.824 cubic centimeters or 0.3553 cubic inches are required per larva which is an overestimate due to the utilization of only the bottom half of the bin.

$$56\ cm * 40\ cm * 13\ cm = 29{,}120\ cm^3 * \frac{1\ in^3}{16.39\ cm} = 1{,}777\ in^3 * \frac{1\ ft^3}{1{,}728\ in^3} = 1.028\ ft^3 \quad (14)$$

$$\frac{29{,}120\ cm^3}{5000\ larvae} = 5.824\frac{cm^3}{larvae} * \frac{1\ in^3}{16.39\ cm} = 0.3553\frac{in^3}{larvae} \quad (15)$$

In a closed system, like the one mentioned above, more strategizing and more space would be required. Each bin would be closed to the potentiality of BSF depositing eggs which would ensure the larvae are all the same age in each bin (Sheppard et al., 2002). Each bin would have the correct amount of food waste added throughout the two-week BSFL consumption stage. In an open system a bin about a few cubic feet in size could host multiple colonies of BSFL and easily handle the 2.76 lb of daily food waste from a four-person household as shown in equation 13 and 16. Equation 13 shows how much larvae would be required for a four-person household and equation 16 shows that only 12 to 13 deposits of eggs from female BSF would be adequate for this compost bin.

$$6{,}261\ larvae * \frac{1\ BSF}{500\ eggs} = 12.52\ BSF \tag{16}$$

Larvae weighed 0.14-0.18 g in the prepupae stage which is when they stop consuming OM (Sheppard et al., 2002). Using an approximate of 0.16 g per larva, food waste from a four-person home could produce 1 kg of larvae per day as shown in equation 17. *Chewy* sells 2,000 larvae for $35.00 (Chewy, 2021). *Grub Terra* sells 500 live larvae for $13.95 (Grub Terra, 2021). *Exotic Nutrition* sells 500 live larvae for $18.95 (Exotic Nutrition, 2021). Shown in Table 1, that is about two to four cents per larva. That is about $30 made a day off 2.76 lb of food waste. This profitability provides incentive to compost as shown in equation 18. The BSFL can be used to feed exotic pets, chickens, and other livestock.

$$6{,}281\ larvae * 0.16\frac{g}{larva} = 1{,}005\ g * \frac{1\ kg}{1000\ g} = 1.005\ kg \tag{17}$$

$$3¢ * 6{,}281\ larvae = \$188.43 \tag{18}$$

Table 1: Price per BSFL from Varying Sources

Company	**Price/BSFL Calculation**	**Price/BSFL**
Chewy	$35.00 / 2,000	$0.02
Terra	$13.95 / 500	$0.03
Exotic Nutrition	$18.95 / 500	$0.04

Large-Scale BSFL Composting

Due to these considerations discussed above, BSFL have potential in bioconversion facilities, because they can handle large amounts and varieties of organic waste while also having other benefits. One being they are a safe insect to work with that can be used as cheap animal feed (Shelomi, 2020). The limits of industrial composting come in the sorting, collection, and transportation of OM to a facility and the later transportation of BSFL products out (Shelomi, 2020). These composting facilities incentivize sustainably handling OM due to the value of BSFL products (Shelomi, 2020).

By comparing traditional composting to BSFL composting, conclusions can be made on which system is more adaptable, efficient, and profitable. The ability to scale these systems up considering economic, ethical, and environmental impacts is key to providing a viable and sustainable waste management process. Industrial composting can become inefficient in its use of energy inputs, space, time, and labor (Makan & Fadili, 2020). Entrepreneurs are using BSFL more for insect farming than bioconversion of organic waste which still addresses several environmental and social concerns at once (Shelomi, 2020).

Methodology

The larvae in this experiment were fed with fresh food waste and kept in a small-scale compost system in a miniature greenhouse. Food waste and carbon material were added to the outdoor traditional composting system. Comparisons were made over a nine-month period from December 2020 to August 2021. By exploring the data collected from the traditional and BSFL composting systems, conclusions can be made on what type of system will provide incentive for food waste and OM collection for recycling or composting on a small- or large-scale.

Experimental Set-up

BSFL Container Preparation

Figure 1 and 2 shows the plastic bin that was used for egg hatching, larvae rearing, and self-harvesting. It was 1.5 ft by 1.5 ft by 3 ft and was kept closed to avoid continuous culture (Sheppard et al., 2002). BSF eggs were bought online from *Reptiworms* for $35 and added to this bin along with 1 gal of fresh food waste (Reptiworms, 2021). A cloth was added to the top but became unusable quickly, so sheets of aluminum foil sat loosely on the top of the container to provide shade and oxygen. The BSFL composting bin was kept in a closed outdoor miniature greenhouse shown in Figure 3. The outdoor miniature greenhouse has temperature and humidity swings throughout the days and nights as show in Figure 4. An inch wide hose was wrapped once around the inside of the BSFL bin. The hose leads out of the bin and into a separate closed 5-gal bucket. This hose acted as the ramp for the self-harvesting part of the system, which larvae will use to crawl out of the food waste and into a dry and high habitat as they mature (Diclaro & Kaufman, 2009). The part of the hose in the BSFL bin had holes every 2-3 in and the part of the hose leading out of the BSFL bin and into the self-harvesting bucket was whole.

Figure 1: BSFL container and self-harvesting bucket set-up.

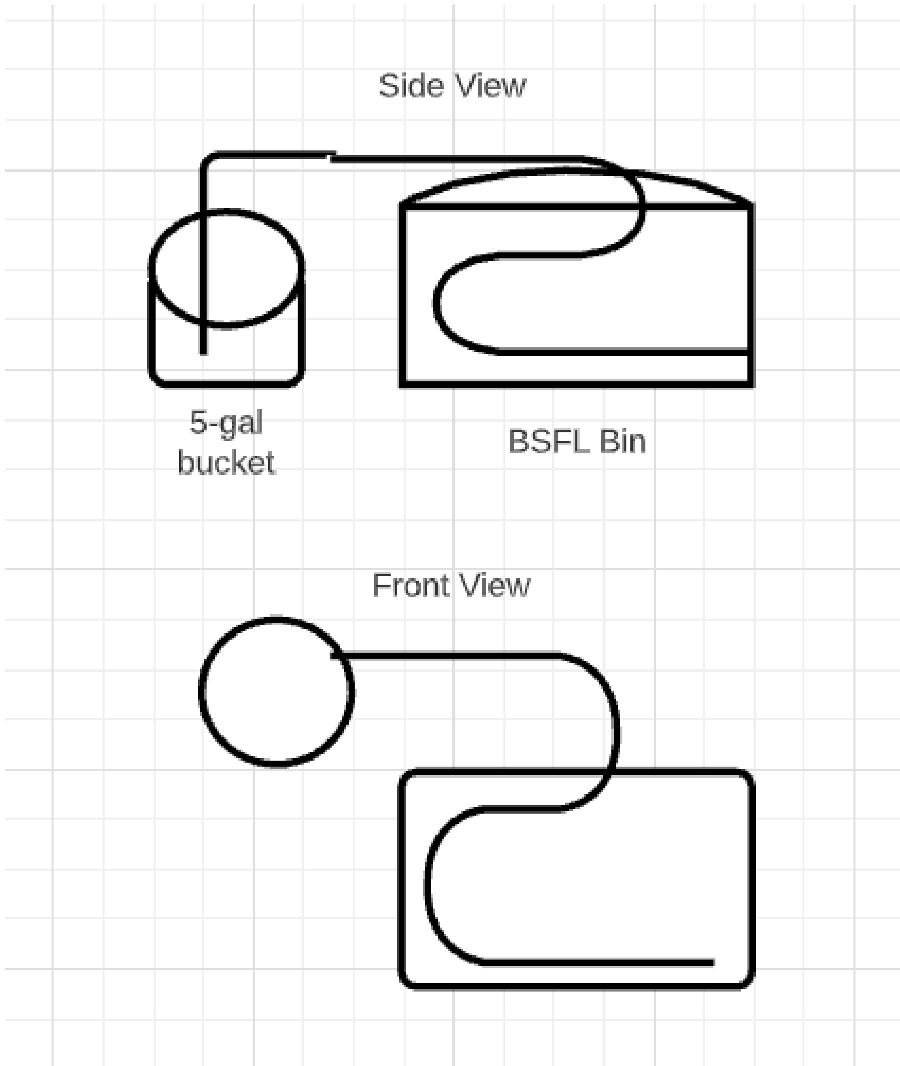

Figure 2: Diagram of BSFL bin including ramp to the self-harvesting bucket

Figure 3: Outdoor miniature greenhouse.

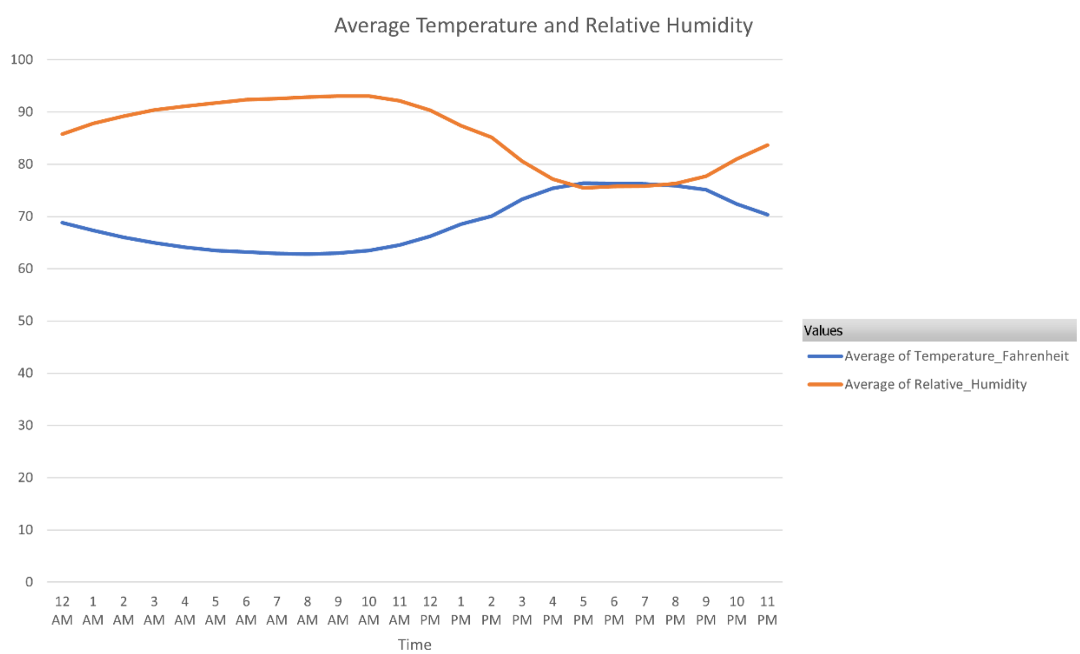

Figure 4: Average temperature and relative humidity inside miniature greenhouse from July 11th to August 9th.

Traditional Composting Container Preparation

A 10 ft chicken wire fence is used as the circumference to a compost bin shown in Figures 5 and 6. The chicken wire and four wooden stakes cost $35 which was the same initial investment as the BSFL set-up. The bin takes up to six months to fill with weekly compost from a restaurant collecting fruit and vegetable scraps, paper products and tea and coffee filters and grounds. Ideally, to have an efficient, actively decomposing compost bin, there should be about 3 to 4 ft in each dimension of waste that is periodically turned for aeration (Gershuny & Martin, 2018).

Figure 5: Traditional compost bin.

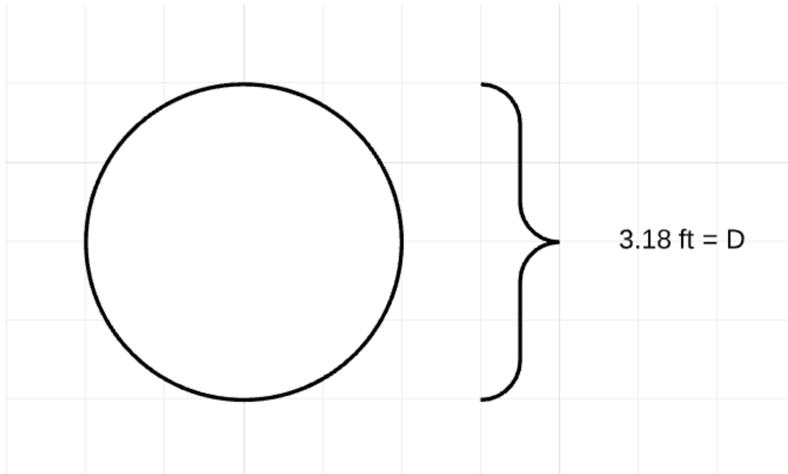

Figure 6: Traditional compost bin dimensions.

Food Waste Inputs

Common fresh food waste contents from one restaurant are listed below and shown in Figure 7. Uncommon food waste contents include paper products, bread, and meat scraps.

- Cantaloupe skins
- Cucumber ends
- Grape vines
- Strawberry tops
- Green onions
- Tomatoes
- Broccoli stems
- Coffee grounds
- Tea grounds
- Paper products
- Bread

Figure 7: Fresh food waste.

Starting BSFL Bin

Using a gram of eggs bought online from *Reptiworms*, the BSFL bin was started by leaving the eggs in an elevated and dry space above 1 gal of food waste (Reptiworms, 2021). A *Govee* Bluetooth humidity and temperature sensor was kept in the miniature greenhouse enclosure recording data every minute. Once the larvae hatched and began consumption, food waste was added periodically. Over the thirty days, six gallon of food waste comprised of the list above were added. The larvae and food waste are pictured in Figure 8.

Figure 8: BSFL and fresh food waste.

Starting Traditional Compost Bin

Food waste and carbon scraps such as dried leaves and paper products were layered from December to July, within the cylindrical chicken wire bin. Over the eight months the compost pile was turned sixteen times, which required twice the amount of space being used by the pile to have room to dig out the compost pile and replace it in the compost bin. To turn the compost, the chicken wire and wood stakes would be pulled away while the compost was shoveled to the side. The chicken wire and wood stakes would then be set back up and the displaced compost would be shoveled back into the cylindrical container. A total of sixty-four 5-gal buckets were added in the first six months of the process.

Data

Variables

The traditional composting system was kept in ambient temperature and relative humidity while the BSFL bin experienced temperature and relative humidity within the miniature greenhouse. The composting method was different for both, allowing independent variables of labor inputs and compost outputs to be measured.

Data Collection

Table 2 shows the values that were tracked to compare BSFL composting to traditional composting.

Table 2: Units and abbreviations of data points.

Measurement	Abbreviation	Unit
Food Waste Inputs	Fw	kg
Compost Outputs	Oc	kg
Larvae Outputs	Ol	kg
Value Per Unit of Compost Outputs	$/Vc	$
Value Per Unit of Larvae Outputs	$/Vl	$

Temperature	t	℃
Humidity	h	g/kg
Time	T	days & months
Labor	L	hours

Temperature and humidity were recorded every minute to observe any changes in larvae or composting processes and compare them with the varying weather patterns. Compost outputs, including finished compost and larvae, are important for determining the value of these two composting processes. The compost from the traditional composting bin was determined as finished when the compost was visually soil-like, with a dark color, and granular, uniform structure, along with an earth-like smell, with no hint of rotting food or anaerobic decomposition (Weppen, 2001). Having a value in dollars for the finished compost and larvae outputs will aid in this comparison. The amount of time it takes to come to a finished product along with labor hours necessary for each composting process will also aid in providing conclusions.

Data Analysis

The collected data was used in the following equations to create comparable values. The units and abbreviations are listed in Table 2.

The hours logged were added together to come to a total amount of days or months to complete the processes of both BSFL and traditional composting.

Also taken from the log, the total amount of time put in as labor is added up in hours to compare between the compost systems. Detail of what types of labor were done are also included in the log. The varying manual labor also affects the level of difficulty during these hours.

The finished compost outputs were shown as a percentage of the inputs using equation 19. The compost outputs for both systems can be used in equation 19 along with the larvae output as well.

$$\frac{Oc\ (or\ Ol)}{Fw} = \ Output\ \% \tag{19}$$

The value of finished compost was calculated below using equation 20. The total value of compost outputs after a certain amount of time and with a certain amount of food waste inputs is in dollars. The cost per unit of compost was calculated and explained in the literature review and in equation 9.

$$Oc * \frac{\$}{Oc} = Total\ Value\ of\ Oc \tag{20}$$

The value of larvae was determined using equation 21. The total value of larvae from the system after a certain time, with a certain amount of food waste inputs and eggs added is in dollars. The cost per unit of larvae was calculated and explained in the literature review, in equation 18 and in Table 1.

$$Ol * \frac{\$}{Ol} = Total\ Value\ of\ Ol \tag{21}$$

Results

The experiment by taking place in Boone, North Carolina, experienced a lower temperature and humidity then ideal for traditional composting and for BSFL. This extended the timeline of both processes. Some parameters and results from each section below are referenced and shown in Table 3.

Table 3: Results and parameters of both the traditional and BSFL composting methods used.

Method	Timeline	Labor Inputs	Compost Inputs	Compost Outputs	Space Use	Monetary Value
Traditional Composting	8 months or 241 days	3 hours	2,431 kg of fresh food waste & carbon	590 kg of finished compost	32 – 64 cubic ft	\$1600
BSFL Composting	1 month or 30 days	40 hours	1 g of eggs 15.6 kg of fresh food waste	4,542 larvae 3.2 kg of leachate	3.4 cubic ft	\$136.20

Timeline

Traditional composting required at least eight months, without energy inputs, before having usable compost for agricultural applications. Starting in the winter delayed the microbial process of breaking down organic matter, therefore prolonging this composting process. BSFL composting required 30 days before a usable product of large, mature larvae could be used.

Labor Inputs

Approximately three hours were spent on BSFL composting over the 30-day timeline, including adding food waste, checking larvae, and setting up the self-harvesting tub and bucket for mature larvae. These were simple tasks especially compared to the labor involved in turning the traditional compost bin. Over eight months it was turned sixteen times which could take up to an hour. This is already five times the hours spent on the BSFL bin and does not include the labor of adding food waste. Overall composting required over 40 hours of labor over the eight months. Even though the traditional composting timeline lasted longer, there were more labor hours over a longer period with compost outputs less valuable than BSFL composting. The manner of the labor also played an important role in the difficulty of maintaining both composting systems. Turning the compost manually required more effort than maintaining the BSFL bin. Another important factor is that the BSFL bin would require a slight increase of labor hours if not the same amount to scale up the amount of waste it could handle. Increasing the amount of waste processed by the traditional bin would create a large increase in labor hours.

Compost Outputs

After eight months the compost bin produced approximately 25 5-gal buckets or 1300 lb or 590 kg of moist finished compost shown in Figure 9. There was a total of 64 5-gal buckets of food waste added to the bin over those eight months. One 5-gal bucket is 0.670 cubic ft, while 1 cubic ft of food waste weighs approximately 25 lb according to the EPA’s (2016) volume-to-weight conversion calculator, which is shown in equations 3 and 4. 64 5-gal buckets weigh approximately 5,360 lb or 2,431 kg. By using equation 19 an output percentage for traditional composting came to 24%.

The BSFL composting system needed thirty days until there were compost outputs. Even though 10 gallons of food waste, which weighed 34.3 lb or 15.6 kg of food waste, were added to the BSFL bin over the 30 days, there was only 7.0 lb or 3.2 kg of a thick liquid which resembled leachate and consisted mostly of water. Using equation 19 an output percentage for BSFL composting came to 21%. When looking at these percentages the changing moisture and structure of compost in the traditional bin which is open to the environment while the BSFL was closed and contained, should be considered. The percentage for the food waste inputs to compost outputs for the BSFL bin would be lower if the leachate was allowed to escape the system. The other compost outputs for the BSFL bin were larvae.

The BSFL bin after 30 days and with 10 gal of food waste added, weighing at approximately 34.3 lb or 15.6 kg, produced 1.90 lb or 0.863 kg of large larvae measuring at an average of 21 mm long shown in Figure 10. Weighing at an average of 0.19 g each there is approximately 4,542 larvae. Using equation 19 there was an output percentage for larvae to food waste inputs of 5.5%.

Figure 9: Finished compost from traditional composting bin.

Figure 10: Finished product of pupating BSFL.

Space Use

The vertical space used changed throughout both traditional and BSFL composting. However, the footprint or surface area used for both stayed the same. The traditional compost bin required 8.0 square ft while the BSFL bin required 4.5 square ft. The BSFL bin required 44% less space to handle only 5% of the compost inputs. When including the vertical space as well, which for traditional composting ranged from three to five feet and for BSFL composting from 0.5 to 1 ft, BSFL composting is favored in terms of space. When comparing the approximate 32 cubic ft used for the traditional compost bin over eight months with and 3.4 cubic ft used for the BSFL bin, the BSFL bin required 89% less space to handle 5% of the compost inputs. Through this comparison it is slightly difficult to see that less space is required for BSFL composting due to the lack of BSFL to handle the same amount of compost that the traditional bin did in 30 days. With 2,431 kg of organic waste added to the traditional compost bin over eight months this is approximately 303 kg every 30 days. If about 4,542 larvae were produced in 3.4 cubic ft or 5,900 cubic in over 30 days, that is approximately 1.3 cubic in per larvae. Each larva handled about 3.43 g of waste over the 30-day period. Every 1.3 cubic in handled 3.43 g of waste, this is about 2.6 g of waste handled per cubic in. The traditional compost bin in 30-days collected 5 to 11 g per cubic in. These values cannot be directly compared due to the immediate bioconversion of waste to larvae occurring in the BSFL composting system while the traditional composting bin acts as a collection process before taking time to convert it into usable finished compost. Another important factor is that traditional composting required twice as much space than the pile was using, in order to turn the pile effectively. The BSFL bin always required the same amount of space throughout the entire process. Taking this into consideration the traditional compost bin collected 2.5 to 5.5 g per cubic inches which is roughly the same as the BSFL bin, even with the BSFL bin handling less waste.

Monetary Value of Outputs

Using equation 20, the value of the compost produced by the traditional composting bin could be up to $1600. This dollar amount is made at the end of the eight months. This revenue excludes the cost of labor, transportation, and initial equipment. This is also a high estimate due to the moisture content of the finished compost.

The BSFL bin produced no finished compost only a thick leachate that weighed 7 lb Using equation 21 the value of the larvae harvested from the bin could be up to $136.20. Over the timeline of traditional composting, the BSFL composting process even scaled up to handle the same amount of waste could have been completed eight times with at least five times less labor invested. This dollar amount would be made every month, instead of like traditional composting where it is made at the end of eight months.

By dividing the value of the composting outputs by the hours of labor, BSFL showed to be $5 more profitable per hour. This does not consider that the BSFL composting system implemented 20 times less waste than the traditional compost bin, and still had a higher hourly profit. This does not include how scalability works with these composting systems. This number also does not reflect the more frequent income from BSFL composting. BSFL composting has the potential to be easily scaled up with small increases to the labor hours and initial investment. Scaling up traditional composting would only be worth it by investing in machinery for compost turning and transporting. Larger BSFL composting facilities do not necessarily require machinery and could be operated manually.

Traditional Composting

Overall requiring months of time to collect and turn the compost, traditional composting in Boone can take up to a year to get a finished, usable compost heap. The labor hours consisting of taking time to collect the compost, add it to the bin, turn it, and use it, can add up to at least five hours a month. Increasing the amount of OM handled by the system proportionally increases space, labor hours, and costs involved in traditionally composting.

BSFL Composting

Providing frequent composting outputs high in value, BSFL composting is a viable solution to wasting food and organic matter. It incentivizes composting by lowering labor inputs, shortening the process, requiring less space, and raising its value. This is because scaling the system up and increasing the amount of OM handled does not necessarily increase labor hours or costs and adds only a slight amount to space required.

Conclusion

Throughout the composting process for both systems, there were continuous indicators that these were two very different systems. OM inputs were different due to the excessive need for carbon material when traditionally composting. In an in integrative composting facility, both traditional and BSFL composting could be implemented to handle different waste streams. Subsequently the bioconversion of organic waste could provide a variety of products.

In conclusion, traditional composting required a larger amount of labor, time, space, and inputs to reach a finished product. BSFL composting provided a more valuable product with less labor, time, space, and compost inputs, making the addition of BSFL in composting highly beneficial.

Discussion

The conditions and setup of this experiment dependably reared larvae, however improvements can be made. It would be helpful to have optimal temperatures for all BSFL stages of life. The additions involved in creating a specific environment for larvae rearing will also raise costs and energy use (Sheppard, 2002).

Even though traditional composting can take less than 6 months, in Boone's climate it almost always takes longer. The use of season extension technologies such as greenhouses are an important part for year-round composting in cooler climates (Schiller & Plinke, 2016). Because the space and labor requirements for cultivating BSFL are less than traditional composting, they are easier to manage in year-round composting especially in greenhouses and underground spaces. By implementing the correct greenhouse design for a specific climate, the greenhouse can stay in desired temperature ranges all year long with little to no energy inputs (Schiller & Plinke, 2016). BSFL do emanate a pungent smell which could disincentivize having them in closed environments such as greenhouses, but that is small setback. BSFL not only incentivize small- and large-scale composting by decreasing the amount of space, labor, and time to reach a valuable product created by recycling, an otherwise trashed, resource. They also have more potential to support year-round bioconversion of food waste and OM due to traditional composting requiring larger amounts of space and high temperatures.

Not only can BSFL be used in the bio-treatment of OM but also provide protein- and fat-rich biomass for use as animal feed and even biooil or biodiesel production (Pang et al., 2020). There is even use for them as human protein supplements (Shelomi, 2020). Moreover, these explorations of using BSFL in other applications showcases the variety of uses for BSFL, making them a dynamic and valuable product, especially compared to finished compost.

BSFL are dynamic in their end use but also in their implementation. Continuous culture methods with BSFL in manure management systems would be beneficial in closed animal housing (Sheppard, 2002). Instead of focusing on bringing OM to larvae, the larvae can be brought to livestock housing and be used for waste management.

Scaling up composting for municipal bioprocessing can put the sustainability of the system into question. Large-scale traditional composting systems require energy inputs to mechanically turn, aerate, monitor, maintain, and transport compost. The use of BSFL in composting has the potential to replace turning compost due to the free movement of larvae as they consume OM (Makan & Fadili, 2020). The sustainability of composting can also be increased with the use of BSFL by providing short-term carbon and nitrogen sequestration rather than the release of them by microbes during the decomposition process in the form of gases (Pang et al., 2020).

Conclusion

Overall, BSFL have a dynamic variety of uses in implementation and end-use, making them a large topic of conversation when discussing sustainable alternatives to real-world problems of unsustainable and linear industrial processes. Traditional and BSFL composting can efficiently recycle OM into soil amendments while the BSFL add value of the bioconversion process. Cultivating BSFL through composting then also provides a protein- and fat- rich biomass accepted as a substitute for animal feed. Additional research on BSFL composting is still necessary but the benefits are obvious and the exploration of implementing them in waste management systems is currently happening.

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