Evaluating the Feasibility of using Screw Conveyors as a Means to Continuously
Grow Black Soldier Fly Larvae

by

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Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2018

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May 9, 2014

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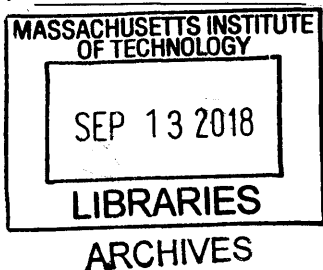
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ABSTRACT

This research attempted to assess the feasibility of using screw conveyors as a means of continuously rearing black soldier fly larvae. Farming of the black soldier fly (BSF) has gained popularity in recent years as means to supply protein for animal feed and recycle food waste. However current methods for BSF farming are labor intensive and costly. This is due partly from the batch system in which BSFs are grown. It is also a factor of space inefficiency, as BSF larvae can only live in the first 7-10 cm of the substrate they are grown in due to oxygen depletion. Screw conveyors in theory could solve both these problems by allowing for continuous production and mixing which could aerate the substrate preventing oxygen depletion. In order to test the feasibility of using screw conveyors an analysis was done to predicted energy cost. Based on the calculations done in this work energy cost would be trivial, on the order of 0.01 US dollars or less per pound of dry weight BSF larvae. Physical experiments were also done on the effectiveness of mixing in aerating the substrate and allowing BSF larvae to live deeper. This involved filling a tube with substrate and BSF larvae to various depth between 15 and 45 cm and measuring oxygen levels at the bottom depth. The tube was also flipped to simulate mixing. While there is a high level of uncertainty, the results in general indicate oxygen was depleted in the substrate on the order of 5-10 minutes for depths bellow 15 cm. This does not support the feasibility of using screw conveyors for BSF farming as the conveyor would have to be running almost constantly to prevent the development of anaerobic conditions. However many factors in this research where high conservative and the development of anaerobic zones in BSF substrate and the effects of mixing warrant further research.

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1. Introduction

In recent years there has been substantial increased interest in insect farming. There are many who believe insects raised for food or animal feed could increase the world's food security, providing much needed protein in an efficient and environmentally friendly manner. In particular, the farming of *Hermetia illucens*, the black soldier fly (BSF), has increased substantially as a source of protein for animal feed. There are now several facilities around the world growing BSFs on a large scale for animal feed [1] [2] . However there are still major challenges facing this fledgling industry.

One of the major challenges of farming BSFs is that the current methods of rearing BSFs have high operational costs, as well as high labor requirements[3]. There are several methods for rearing BSF larvae, but the vast majority of farms use a relatively simple system where the larvae are placed in bins and feed is periodically added, usually some form of food waste. Moving the bins and feed as well as harvesting the BSF Larvae from the bins is the main labor sink. Space efficiency is also an area of concern as BSF can normally only live in the top 7-10cm of feed substrate due to oxygen depletion below this. This means either many shallow bins must be spread out over a large area or stacked vertically. Increased levels of automation are required in order to make the current methods economical. It is likely that entirely new systems will need to be developed if BSF farming is ever going to take place on an industrial scale.

This research proposes a novel method of rearing BSF larvae that allows for continuous production. The methods involves growing the larvae in screw conveyors. A screw conveyor,

like all conveyors, allows BSF larvae and their feed to be transported without labor. By attaching paddles to the screw conveyor shaft, the conveying motion could simultaneously mix the substrate, provide aeration, and release heat. This should enable the BSF larvae to live deeper than 10 cm in their feed substrate, allowing the screw conveyor to have a large diameter and increasing space efficiency. Screw Conveyors also tend to be less expensive than other types of conveyors.

In order to analyze the feasibility of using screw conveyors, a cost analysis was conducted. Using an accredited manual for designing screw conveyors, the energy usage and associated cost were estimated for screw conveyors with varying parameters. The initial capital cost of purchasing a screw conveyor was also roughly estimated. Based on the calculations, energy costs from the screw conveyor would be relatively minimal. In a worst case scenario the energy costs were on the order of one cent per pound of BSFs produced.

Physical testing was also undertaken to determine how effective mixing would be at aerating the substrate and enabling the BSF larvae to live deeper. A test set up was constructed that mixed substrate and allowed for oxygen level testing at various depths.

2. Background

2.1 The Black soldier Fly

2.1.1   Use in Industry

The black soldier fly has been adopted as the insect of choice in mass rearing for animal feed. The BSF has several qualities that make it so appealing. The first quality is that the larvae

can be grown on a wide range of inexpensive feed stocks including food waste and manure. It has a good feed conversion ratio, "FCR," around 2 [4], as well as a good efficiency of conversion of ingested food (ECI) of around 25%[4]. It also has a high growth rate, going from an egg weighing 0.028 mg[5], to a mature larva weighing 120 -157mg (48-63mg on a dry weight basis), in 15-20 days[6]. BSF larvae also have the ability to self-harvest as mature BSF larvae naturally travel away from their food source when they are ready to pupate.

2.1.2 Life Cycle

The black soldier fly is native to North America. It has three life stages larvae, pupa and adult. The larvae is the main life stage and last 14 -30 days depending on temperature and conditions [7]. Larvae are white/brownish in color and resemble fly maggots. During this time the larvae goes through seven instars before transforming into a pupae. In the last instar the larvae turns dark black and develops hooks on their jaw. This allows them to climb out of their food source to a dry place. The pupal stage lasts about a week, after which the adult BSF emerges. Adult BSFs resemble black wasps and live for around two weeks. During this time they don't consume any food and focus on mating and finding a suitable place to lay their eggs. Female BSF lay between 200-600 eggs and prefer to lay their eggs above or near the larvae's intended food source rather than directly in it. There has been a lot of research into inducing BSFs to mate in artificial environments. For a while this was a limiting factor in the industry, but has since been solved by all the major companies [8].

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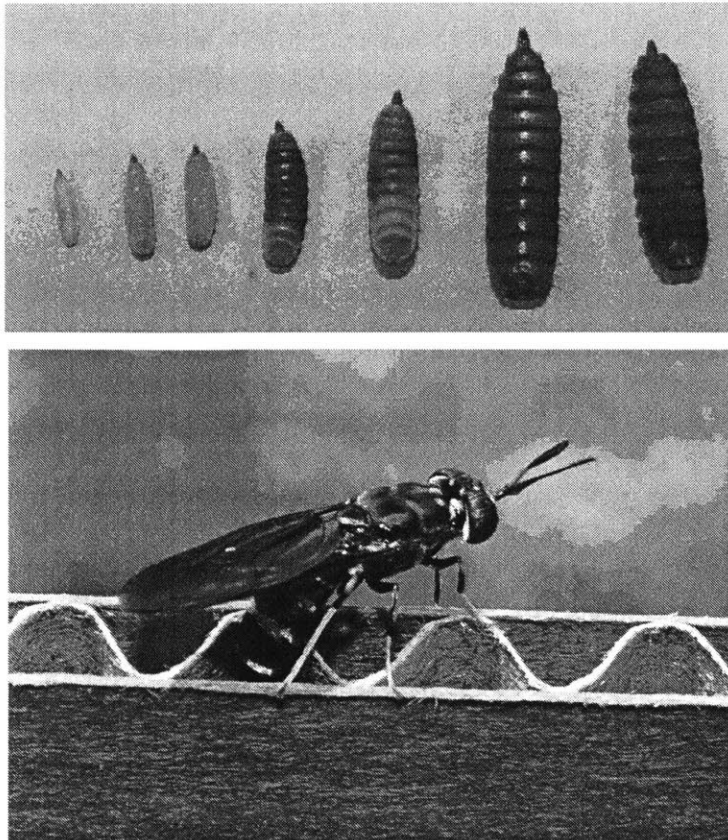
Figure 1. The top image shows six of the seven instars of the black soldier fly larvae stage. The larvae on the top right is actually the pupal stage. The bottom image depicts an adult black soldier fly. The top photo was taken by Jonathan Tan.

2.1.3 The Current Farming Systems

BSFs have been studied for many years as a means of waste management, however only recently have commercial plants growing BSFs come into existence. Due to their relative novelty, there is very little information on the current systems in place for growing BSFs. Most of the companies in existence are reluctant to share information about their systems for BSF farming. The following describes the current systems in existence based on information that can be gathered from published studies, patents, company websites and interviews.

There are currently two systems used to grow BSFs. The first is not widely used in large scale farms but is common for small privately owned units. In this system BSF larva or eggs are added to large bins along with food waste or manure. The BSFs spend their entire time in this one container, usually 2 -3 weeks[6]. Once the BSFs are ready to pupate they will seek a dry place away from their feeding area. The bins are designed to allow the BSFs to crawl out of the bin into a collection bin when they are ready to harvest, effectively self-harvesting themselves, and this is often referred to as crawl off. New BSFs larva/eggs and feed stock are continuously added to the bin to replace the mature larvae leaving the bin and the food being eaten. The refuse is cleared out on a semi regular basis. The details of this system are hard to come by, like the frequency of feeding and refuse clearing, and the rate of crawl off vs the rate of eggs added to the system

This system is often referred to as the continuous system for BSF farming. The benefits of this system are its simplicity and minimal labor requirements [2, p. 6]. It also doesn't require a harvesting/sifting machine. The draw backs are that it is susceptible to outbreaks of disease and can be difficult to manage since there are BSFs of all ages and sizes in the bin simultaneously [2]. The refuse that is uneaten by the BSFs also has to be periodically cleared out. This buildup of refuse is what facilitates the growth of pathogens and harmful fungus. Enviroflight, a company using an alternative system, also stated that the BSF crawl off can be rather unreliable. The company elaborated that BSFs may crawl off prematurely or sometimes don't crawl off at all, especially if the feed stock is on the dry side.

The second system, which is the one used by most of the industry, is the batch system. In this system, BSF eggs are hatched in a nursery and the young larva are raised in small container for 3-7 days. After this initial period, the BSF larva are transferred to a larger bin where they stay

for about 2 weeks before being harvested. During this time they are periodically fed either with machinery or manually. In theory the BSF could be transferred to larger bins multiple times for better space efficiency, however this would also increase labor costs. Bin size varies widely from company to company. Enviroflight uses large steel troughs, 3.5 ft. by 2 ft., whereas Protix, who is one of the few companies with a patented system, uses many small shoe box sized containers stacked on top of each other [9]. Since the BSF are more separated and bins are routinely emptied and cleaned with each harvest, this system is less susceptible to disease than the continuous system. It is also generally easier to control and monitor. However the labor costs for the batch system are higher due to the need to manually inculcate, feed, and harvest multiple bins (cite book). There has been almost no published research on batch systems and the companies that use them all have slightly varied systems, of which the details and important statistics are generally kept secret. Enviroflight stated in an interview that with their batch system, one 7 sq. ft. bin could produce 650 lb. of wet larvae (270 lb. dry larvae)/year. And that labor costs for a manual batch system are around $0.3/lb dry weight for the growing stage. They also stated that labor cost and space were the two major limiting factors in a batch system such as theirs. Researchers of BSFs observed that a batch system using food waste could produce 145g of dry BSF per m2 per day with a feeding rate of 3-5kg/day[6]; this is roughly one third of what Enviroflight's system claims.

For both the batch and continuous systems, one of the limiting factors is that BSF can usually only survive 7-10 cm from the surface of the substrate in which they are living, as below this the substrate becomes anaerobic. This is largely due to water accumulating at the bottom of bin. Almost all BSF bins are designed with a drainage system for this reason. Due to this relatively thin margin in which BSFs can grow, most BSF farmers stack multiple shallow bins on

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top of each other. This increases space efficiency but also makes feeding and harvesting much more complicated. There are currently 2 patents for growing BSFs stacked in many shallow containers, including one that can operate as a conveyor belt[10][9]. Another solution is to use large drum containers that rotate periodically or continuously to aerate the substrate. This system has been patented and has potential, though none of the current BSF companies are using this technology[11].

2.2 Background on Screw Conveyors

There has been considerable research into predicting the energy requirements of screw conveyors. Predictions vary widely due to different systems. The following is a summary of the process to predicting screw conveyor power requirements based on the KWS manual[12].

There are two elements that contribute to the power requirements of a screw conveyor. The first element is the friction horse power (FHP). This is the energy required to spin the conveyor while empty. The second element is the material horse power (MHP), which is the energy required to move the material, along the screw conveyor.

FHP is a factor of the diameter, speed, length, and bearing type; it can be calculated using equation 1. The diameter factor (DF) is correlated to different standard screw diameters and has been experimentally determined through testing. It can be looked up in the diameter factor table. Hanger bearing factor (HBF) has also being experimentally determined for different types of bearings. For example steel ball bearings have a hanger bearing factor of 1, and nylon bearings have a factor of 2. FHP is directly proportional to speed and length, which are in units of rpm and feet respectively.

Eq.1 FHP = friction horse power (hp), DF = diameter factor (-), HBF = hanger bearing factor (-), L = length (ft), S = speed (rpm)

$$FHP = \frac{DF \times HBF \times L \times S}{1,000,000}$$

MHP is calculated using equation 2. MHP is directly proportional to the Capacity (CP), material factor (MF), and length. Capacity is the mass flow rate in lbs/hour. Material factor has been experimentally determined and can be looked up based on the material being conveyed. If the material in question doesn't have a material factor it is recommend to use the material factor of a similar material.

Eq.2 MHP = Material Horse Power (hp), CP = capacity (lbs/hr) MF = material factor (-), L = length (ft).

$$MHP = \frac{CP \times MF \times L}{1,000,000}$$

When designing a screw conveyor, capacity is generally converted to required capacity in cubic feet per hour (CPH), by dividing by the material bulk density (W), as can be seen in equation 3. This is then multiplied by the capacity factor (CF) which is related to the pitch, to find the selection capacity (SC). Standard pitch flights have a capacity factor of one. Half pitch flights have a capacity factor of 2.

Eq.3 CPH = required volumetric capacity (ft^3/hr), CP = required capacity (lbs/hr) W = bulk density.

$$CPH = \frac{CP}{W}$$

Eq.4 SC = selection capacity, CF = capacity factor.

$$SC = CPH \times CF$$

When loading a conveyor there are three recommended trough loadings, 15% , 30% and 45% , this corresponds to how filled the trough is. These loadings are standard for screw conveyor design. The trough loading is chosen based on the material, generally the denser and more difficult the material is to convey, the lower the trough loading. Using the trough loading and the selection capacity, the correct diameter is chosen based on the capacity at one rpm (CP1rpm) for possible diameter options. Capacity at 1 rpm has been experimentally determined for different trough loadings and diameters and can be looked up in a table. The speed at which the conveyor needs to operate to meet the original capacity can be determined by dividing the selection capacity by the capacity at 1 rpm, as seen in eq. 5.

Eq.5 S = speed (rpm), SC = selection capacity, CP1rpm = the capacity at one rpm (cubic feet/hour)

$$S = \frac{SC}{CP1rpm}$$

Often times a screw conveyor will not only move material, but also mix it, and in this case paddles are added to the shaft of the conveyor. One to four paddles per pitch can be added. Based on the number of paddles added the MHP is multiplied by an additional special factor (SF), indicating the increase in horsepower. This is depicted in eq. 6.

The total shaft horsepower is calculated using equation 6. The MHP multiplied by the special factor based on the number of paddles and FHP are added and divided by the efficiency (e), which is typically around 0.88. This is used to choose the appropriate sized motor.

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FIRST PADDLE FROM
EITHER END USED
AS COUPLING BOLT

SPACING - 3
PADDLES PER
PITCH AT 120°

VARIABLE DEPENDING
ON CONVEYOR LENGTH

PADDLES TO BE MOUNTED
OPPOSITE HAND OF FLIGHTING

SPACING 1-1/4 PITCHES
APART AT 90° FROM
PRECEDING PADDLE
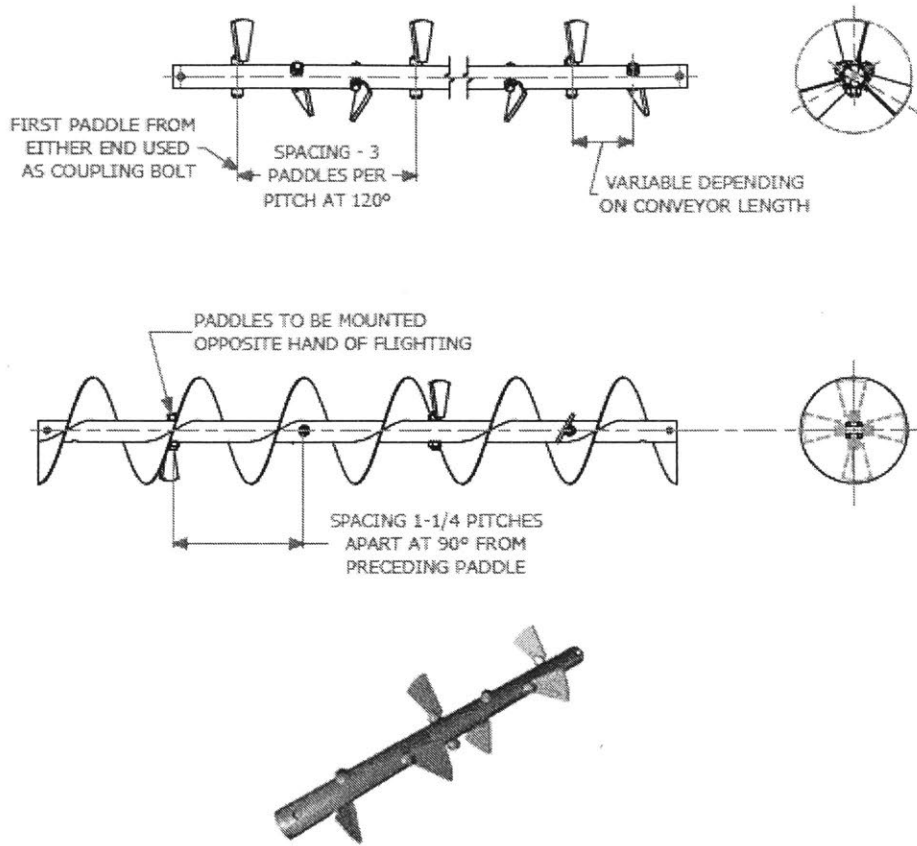
Figure 2. The above images were taken from the KWS manual for screw conveyor paddles[13]. The diagram indicates how paddles can be attached to a screw conveyor shaft to allow for mixing. Higher paddles per pitch indicates a higher density of paddles. The bottom image is a 3D model of paddles attached to the conveyor shaft.

Eq.6 TSHP = total shaft horse power (hp), FHP = friction horsepower (hp), MHP = material horsepower (hp), SF = safety factor (-), e = efficiency (%).

$$TSHP = \frac{(FHP + MHP \times SF)}{e}$$

3. Predicting Energy Cost for a Screw Conveyor Growing BSFs

3.1 Methods

3.1.1 Deriving Energy Equation

The calculations done in the previous section would likely still need to be done to some extent when designing a screw conveyor to grow BSFs. However when growing BSFs, the length and mass flowrate through the conveyor are not the main concern. The main concern would be energy usage per unit mass of BSF produced and whether the screw conveyor could effectively aerate the substrate.

Assuming that a screw conveyor with a paddle design could effectively aerate the substrate while spinning, the next question would be how often the screw conveyor would need to spin in order to keep the substrate aerated. For the purpose of this work, this is captured in a new variable, revolutions per minute (RPM), which defines the frequency/average speed.

Using the standard formulas for predicting horse power and the new variable revolutions per hour a formula for the energy use per day per unit length can be derived. Using equations 3, 4, and 5 material horse power can be related to speed through CP as seen in eq. 7.

Eq.7 CP = capacity (lbs/hour), CP1rpm = capacity at 1 rpm (ft^3/hr), W = bulk material density (lbs/ft^3), CF = capacity factor (-)

$$CP = \frac{S \times CP1rpm \times W}{CF}$$

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By plugging this value in for CP in the MHP equation the TSH is now a factor of S, the operating speed of the conveyor. For the purposes of energy calculations, S can be substituted for RPM. The TSH equation can now be written as the average power required per unit length (APR) by substituting in the FHP and MHP in terms of RPM. This is converted to kWh per day as this is a more relatable unit to deal with. This is depicted in equation 8.

Eq. 8 APR = average power required per unit length, RPM = revolutions per minute (rpm), HBF = hanger bearing factor, DF = diameter factor, CP_at1rpm = capacity at 1 rpm (cubic feet/ hour), W = bulk material density (lbs/cubic foot), MF = material factor, CF = capacity factor, e = efficiency.

$$APR = RPM \frac{\left(HBF \times DF + \frac{CP_{at1rpm} \times W \times MF}{CF}\right)}{1000000 \times e}$$

$$APR\left(\frac{kWh}{day}\right) = APR(hp) \times \left(745.699872 \frac{W}{hp}\right) \times \left(86400 \frac{s}{day}\right) \times \left(3.6 \times 10^{-6} \frac{kWh}{W}\right)$$

Using the above equation the energy need per unit length of a screw conveyor can be predicted for conveyors at different diameters operating under multiple possible average speeds conveying different materials. The effect of varying the pitch and number of paddles can also be predicted.

In order to find the energy required per unit mass of BSFs produced, the dry mass of BSFs produced per unit length must also be predicted. Based on previous research and information obtained from Enviroflight, BSF production per unit volume can be estimated. Enviroflight claims to be able to produce 270 lbs (dry weight) of BSFs in a 7 square foot bin per year. This correlates to 0.105 lbs produced per square foot per day. Given that BSFs can only survive at a maximum depth of 7-10cm without aeration we can extrapolate that to 0.32 lbs/ft^3. By multiplying this by the volume of the conveyor per unit length and the through loading rate,

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the BSF mass produced per unit length (BSFM) can be predicted, as seen in equation 9. Trough loading of 45% was used exclusively as it was the highest possible loading. In reality, a screw conveyor growing BSFs would likely have a higher loading than 45% for the purpose of space efficiency.

Eq. 9 BSFM = BSF mass produced per ft of screw conveyor (lbs/ft/day), BSFP = BSF mass produced per ft^3 per day (lbs/ft^3/day), D = diameter (ft),

$$BSFM = BSFP \times \frac{\pi D^2}{4} \times 0.45$$

With this the energy use per pound of BSF produced (EPP) can be predicted along with the energy cost per pound (ECPP), based on the typical energy cost (EC) in the US. This is depicted in equation 10.

Eq. 10 ECPP = energy cost per pound(US$/lbs), EC = energy costs (US$/kWh), APR = average power required per unit length (kWH/day/ft), BSFM = BSF mass produced per unit length per day (lbs/ft/day).

$$ECPP = \frac{EC \times APR}{BSFM}$$

3.1.2   Predicting Energy Costs

Using the equation established in the previous section, a script was written to predict energy cost under a multitude of possible conditions. The variables were diameter, revolution per minute, pitch, bearing type, number of paddles, BSF production per unit volume and energy costs. All of these variable have set limits or possibilities except revolutions per minute. Revolution s per minute was set at a nominal value of one revolution per hour. This is on the

same order of magnitude as the previous study by Eby where a rotating bin was used to aerate substrate growing fly larvae and rotated periodically every four hours [14].

The script was run under the worst possible conditions to attempt to conservatively estimate high energy cost. The special factor related to paddles and the hanger bearing factor were set to their maximum value based on the tables in the KWS engineering manual. The capacity factor correlated to pitch which appears in the denominator of the energy equations is set to its minimum value of 1 for standard pitch. Energy cost were set at $0.2 per kWh which is the average energy cost in the Boston area and is on the high side of the national average energy cost. The material properties of the compost were chosen as most similar to the food waste that BSFs are typically grown on. The remaining variables to be tested are diameter and revolutions per minute. Diameter dictates diameter factor, capacity at 1 rpm, and BSF production per unit length. There are eleven standard diameter s for screw conveyors ranging from 4 to 36 inches. RPM ranged from 1 revolution every 4 hours to 4 revolutions an hour. It should be noted these values are in essence guesses, and actual testing will need to be done to determine the RPM necessary for aeration.

Length has been largely ignored for this testing as it is assumed the conveyor can be run backward or forwards in order to aerate the substrate, and can be run continuously forward when it's time to harvest the BSFs. This allows the conveyor to be any length. In reality the length would be maximized for the sake of efficiency, and limited by space or the horsepower of the available motors.

3.2 Results & Discussion

Energy costs were predicted at various diameters and revolution frequencies, and the full results can be seen in figure 3. Under all conditions energy costs remained under one cent per pound. This makes energy costs from operating the screw conveyor almost trivial in comparison to the total cost of growing black soldier flies. While no company interviewed was willing to state their complete costs per pound, it's likely similar to that of fishmeal which is on the order of $1-2 per lb.[15].

Overall there is a high level of uncertainty with the predicted energy costs. While not the worst case scenario, parameters were chosen to be conservative. The formulas used were not intended to be used with a screw conveyor operating at such slow speed and continuously night and day. The loading percentage of 45% was chosen because it was the highest option available but in reality a screw conveyor growing BSFs would want to be operated at over 50% for the sake of space efficiency. The screw conveyor would also need to either operate at very low speed continuously or be able to start from stop while fully loaded which is something typical screw conveyors rarely do.

That said, the predicted energy costs are low enough that even if they were off by an order of magnitude, the energy cost would still likely be low enough to warrant the use of a screw conveyor for the sake of reducing labor, increasing output, and space efficiency.
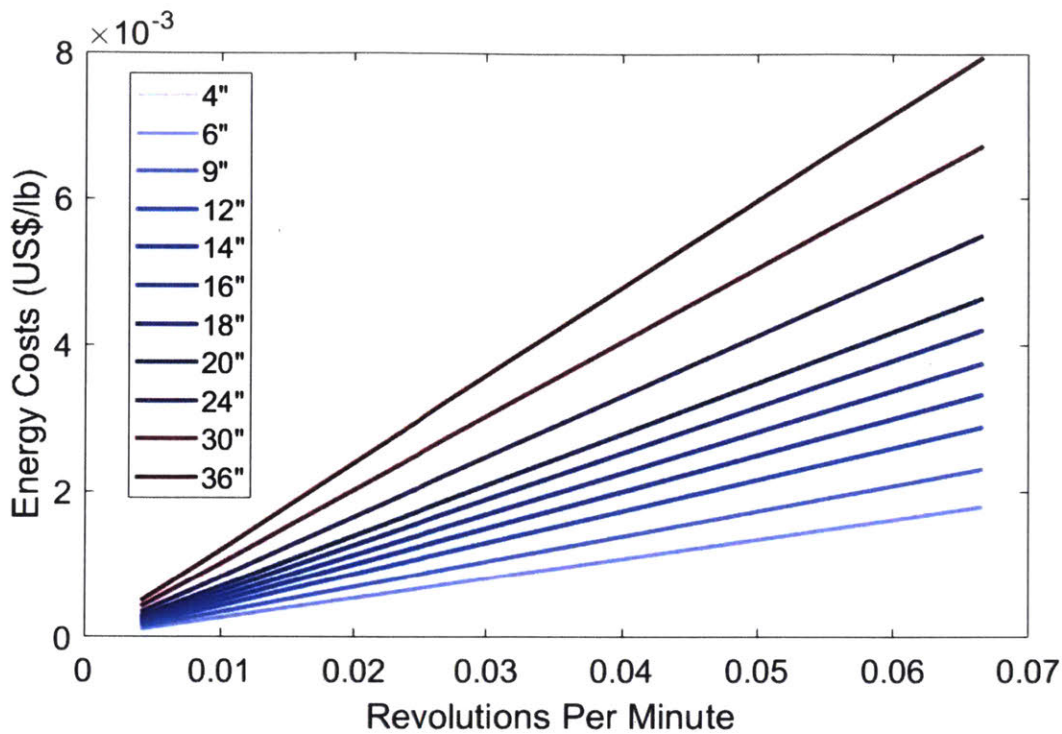
Figure 3. The predicted energy cost for a screw conveyor growing BSFs is shown versus the conveyors operating revolutions per minute. Each line indicates a possible screw conveyor diameter. Energy cost increase with both diameter and speed but stay below 1 cent per pound.

4. Measuring oxygen in substrate Growing BSF Larvae at Various Depths & and the effects of mixing

4.1 Experimental Design & Methods

It is common knowledge in the industry that BSF Larvae cannot be grown in feed substrate more than 10 cm deep due to the development of anaerobic conditions. In order to quantify this effect a simple experimental set up was constructed for measuring oxygen levels at various depths of substrate growing BSFs.

The main setup consisted of a 5.1 by 5.1 by 101.6 cm acrylic tube with 0.3 cm walls in which BSF larvae with feed substrate could be grown at varying depths. There was also a short 35cm tube used for smaller scale tests. The larger tube was mounted on an axel at the center so it could be flipped to simulate mixing like that which would occur in a screw conveyor. Holes were drilled at 3.0 cm and 10.0 cm from each end of the large tube to attach 1/2" PVC elbow connectors which in turn could attach to oxygen gas sensors. For the smaller tube, only one PVC elbow was attached 3 cm from the bottom. A CAD model of the experimental set up is depicted in figure 4. PVC connectors were glued on and sealed with epoxy to prevent any air leakage into the tube. Vernier O_2 gas sensors were attached to the PVC fitting using 2.54 cm ID, 0.4 cm thick PVC tubing, as is depicted in figure 4. The fitting was necessary as this type of oxygen gas sensor must be operated vertically. The ends of the tubes were sealed off using vinyl end caps. These were wrapped with e-tape to minimize air leakage. A small hole was drilled in each end cap such that a temperature sensor could be inserted with a rod 7 cm into the tube. The hole also allow leachate to drain. The testing tubes where contained within a 122 by 122 by 25 cm enclosure which was heated to approximately 28 °C. BSF larvae show optimal growth and survival between 27 and 30C[7].
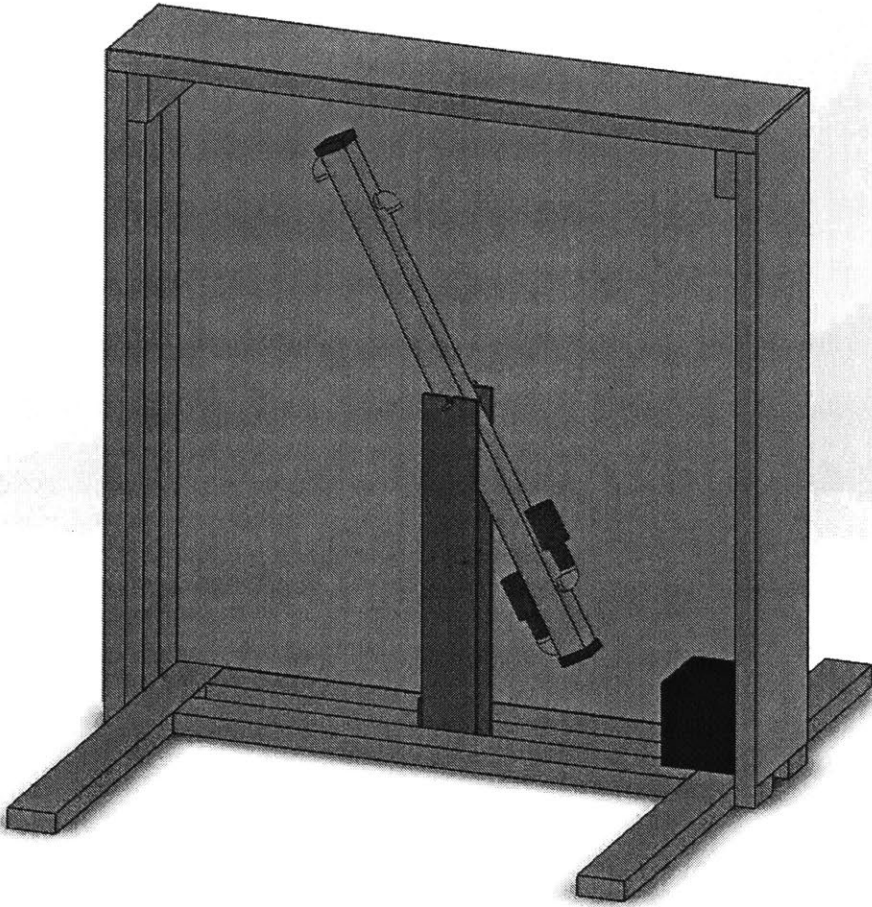
Figure 4. CAD model of the experimental setup. During experiments the structural frame was covered in a tarp such that the inside could be heated.
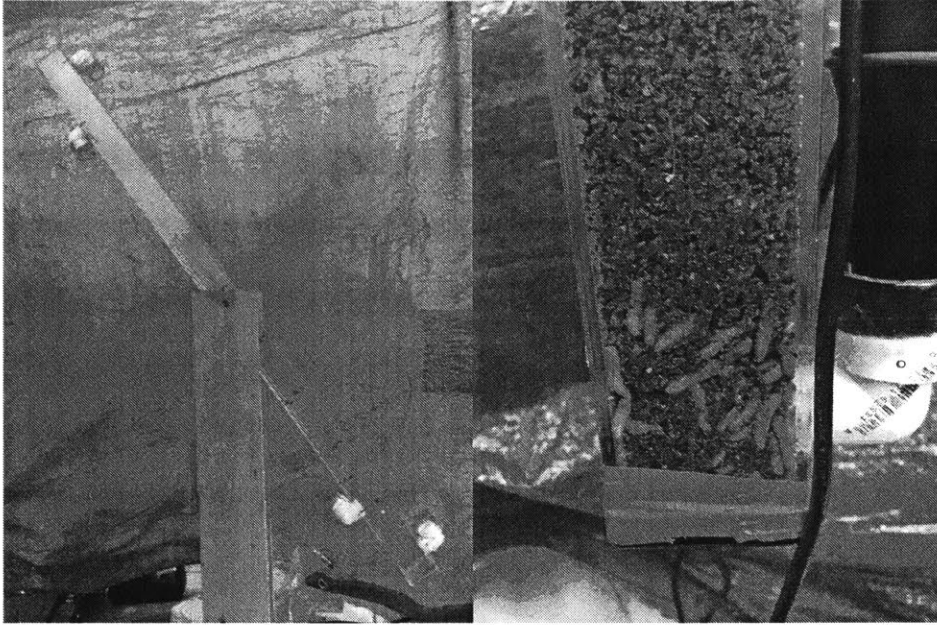
Figure 5. To the left is a photo of the testing tube used in the experimental set up. As seen it was mounted on an axle to allow it to be flipped to simulate mixing. To the right is a photo of the bottom of the tube when filled with larvae and substrate. The PCV connector to the oxygen sensor can also be observed. Note the connection with clear PVC tubing between to sensor and the PVC elbow. This connector and elbow was necessary as the oxygen sensor only operated vertically

The BSFs where grown on a diet that contained 80% wheat bran and 20% cornmeal, which was mixed with water at a ratio of 10g:17 ml water. This composition is similar to the Gainesville diet which has been used in previous studies on BSF larvae rearing[16] [17]. BSFs are usually grown on a diet of food scraps or waste such as brewer's grains. However food scraps can be highly variable which is why the grain based diet was chosen for the purpose of repeatability and comparing experiments. This diet is also similar to a diet of brewer's grain. Larvae were purchased from Fluker Farms under the category of small and ranged between 5 and 10 mm in length.

Prior to the start of all testing, the feed substrate and larvae were placed in the enclosure for 1 hour at roughly 28 °C in order to warm up. Also prior to testing the oxygen sensors where calibrated assuming an ambient oxygen level of 20.9 %. In reality it was probably slightly lower due to humidity

Preliminary tests were conducted with the smaller tube to observe the rate of oxygen depletion just below 10 cm. For the preliminary tests approximately 1000 larvae where mixed with 80 grams of feed in a shallow tray and then poured into the tube. This feeding rate was chosen as it was in the range at which larvae were fed in a previous study done by Sheppard[16]. The height of the substrate above the oxygen was measured with a ruler from the center of the PVC joint to the top of the substrate. Oxygen levels where monitored at a sampling rate of 1 sample per 5 seconds until a clear steady state value had been reached. Temperature inside the substrate was also recorded. The variables of interest were the rate of oxygen decline, the final steady state oxygen percentage, and when/if oxygen levels dropped below 2.0%, approximately anaerobic.

After preliminary tests the large tube was used. This tube allowed for oxygen measurements at two depths. However one of the two oxygen sensors available for this test began to malfunction midway through testing, therefore most results were taken at the lower measurement site. For these tests 2000 larvae were used from the previous test along with their old substrate. Additional new substrate was added until there were 2000 larvae within one liter of substrate, such that there were approximately two larvae per cubic cm. This density was chosen as it was close to the density at which Enviroflight stated they grew their larvae, which was approximately 1.5 adult larvae per cubic cm. The combination of larvae and substrate were then mixed in a shallow pan and poured into the large tube.

Testing proceeded in the same manner as in the preliminary testing. The mixture of substrate and larvae were poured into the tube until the desired depth of substrate was reached. For these experiments, substrate depth varied between 25 and 45 cm. Tests were run for 30 minutes. Preliminary tests indicated this was sufficient time for the oxygen levels to reach a steady state value. In some cases testing was cut short if it was clear that conditions had become highly unfavorable in the tube, indicated by a large number of larvae attempting to escape. After 30 minutes the oxygen sensors were moved to the opposite end and the tube was flipped 180 degrees, allowing the substrate and larvae to fall to the other side. Due to the small cross section of the tube, the substrate tended to stick to the tube's sides and the tube had be to be shaken slightly in order for the substrate to fall.

The process of pouring simulated a perfect form of mixing where all the substrate was subjected to aeration before entering the tube. Flipping the tube was meant to simulate a more imperfect form of mixing, as would be more likely in a screw conveyor where some of the substrate would stay relatively compacted and unexposed to the air.

After flipping the tube, oxygen and temperature levels where monitored for 30 minutes or until it was clear conditions had become unfavorable. The new substrate height after flipping was measured as it was usually slightly lower than the original test due to the substrate condensing and some of the substrate and larvae getting caught in the PVC elbows. Once testing was finished, the larvae and substrate where poured out of the tube and stored in a shallow container at room temperature.

4.2 Data Analysis

For the trials $O_2\%$ and temperature were recorded with respect to time. An example of the data collected for an experimental trail is depicted in figure 6. $O_2\%$ tended to have a small region of negative concavity at first, followed by a region of linear decrease and then a final stage where it approached its steady state value, as can be observed in figure 6. Using linear interpolation over the region of constant oxygen decrease, the rate of oxygen decline was determined. This is also depicted in figure 6. The steady state value was also determined by averaging the final region where O_2 % was approximately constant. The times at which oxygen levels dropped below 2.0% was also recorded as this indicated conditions had become anaerobic. For some of the preliminary tests oxygen levels never dropped below 2.0%, and this is noted in the results. Temperature tended to increase slightly over most experiments. The average temperature over each experiment was recorded.
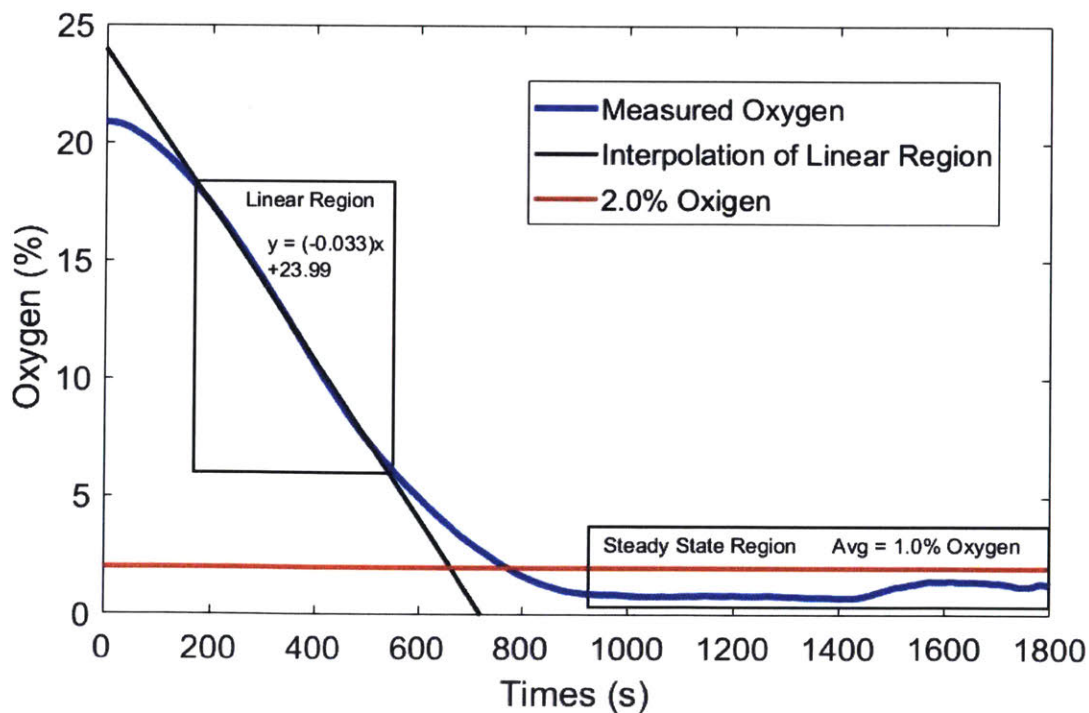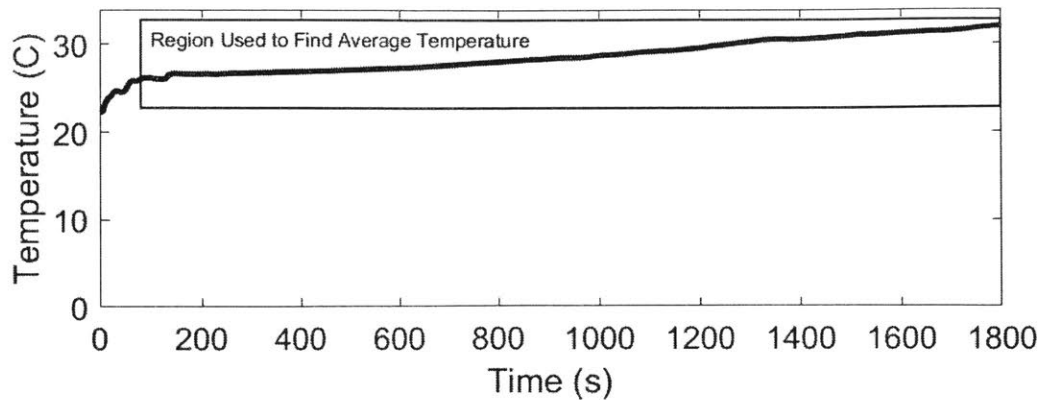
Figure 6. The top graph depicts the measured O_2% in one of the preliminary experiments with respect to time after the feed substrate and larvae were added to the tube. The first box depicts the linear region used to measure the rate of oxygen reduction in the substrate. The second box indicates the steady state region which was averaged to get the steady value. The red line indicates the 2.0% oxygen level, the time at which the measured oxygen level dropped below this value was recorded. The bottom graph depicts the temperature inside the test tube with respect to time. The box region indicates the values used for the average temperature over the experiment. The initial transient values right after the tube is filled with substrate are omitted.

4.3 Results and Discussion

The results for the preliminary conditions are depicted in table 1. It was difficult to keep all parameters constant throughout experiments. The major parameters that varied were days since the BSF larvae were originally mixed with their substrate, which will be referred to as the age of the substrate, and average temperature in the tube throughout the experiment. These parameters are recorded for each experiment in table 1.

Depth varied little in these experiments, yet all the results varied substantially. While average temperature varied to some degree the variable that seemed to affect the results the most

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was the age of the substrate. Moreover, substrate that was one day or older tended to have much

lower steady state oxygen levels and higher rates of O_2% decrease. Also oxygen only dropped

below 2.0% in the experiments where substrate was 1 day or older. This was taken into

consideration for the final experiments. Substrate that was 1 day or older would be more realistic

of what would be used in screw conveyors. All final experiments were done with substrate that

was 1 day or older.

Experiment	Oxygen Sensor Depth (cm)	Average Temperature (C)	Age of Substrate (Days)	Steady State Oxygen Level (%)	Rate of Oxygen % decrease (-%/min)	Time at which Oxygen Dropped Below 2.0% (min)
1	15	30	0	7.4	0.23	Na
2	14	31	1	1.0	2.1	11
3	16	28	0	4.7	0.44	Na
4	13.5	29	2	1.0	2.0	13
5	15	29	0	6.1	0.39	Na
6	13	31	3	1.9	1.3	26
7	16	29	1	0.9	1.606	13

Table 1. The experimental conditions and results for the preliminary experiments are
listed above. The experimental conditions were Oxygen Sensors Depth, Average
Temperature and Age of Substrate. The results are Steady State Oxygen Value, Rate of
Oxygen Decrease and Time at which Oxygen Dropped Below 2.0%. Na indicates the
oxygen levels never dropped below 2.0%.

Observing the trials done with substrate that was one day or older, we see that the rate of

O_2% decrease was on the order of 1-2 % per minute. The time at which the substrate became

anaerobic signified by the oxygen level dropping below 2.0% for these trials was on the order of

10 to 15 minutes. The one notable exception being experiment 6. This was the oldest experiment

conducted and it's possible the larvae might have run out of edible substrate and their

metabolism slowed down. However the exact reason for the increased time till the development

of anaerobic conditions for this trial is unclear. With new substrate the steady state oxygen levels never became fully anaerobic even though the substrate depth was over 10 cm.

Table 2 lists the final experimental conditions and results. The age of the substrate is not listed, as all substrate used for the final experiments was older than 1 day. The mode of aeration is listed as either poured or flipped. Flipping was an imperfect aeration method meant to more accurately simulate the type of mixing that would be expected in a screw conveyor. As in the preliminary experiments it was clear there were many factors affecting the conditions in the testing tube other than depth, temperature and mixing method. There were unfortunately also several cases where data was missed due to errors, or equipment malfunction.

While the data may be uncertain it does provide some insight into the phenomena of the development of anaerobic conditions in BSF substrate. The steady state level of oxygen for all experiments was below 2.0% and in all but the most favorable condition was under 1.0%. It should be noted that the sensor itself, when calibrated as mentioned in the materials section is only accurate within +/- 1.0%.

The rate of oxygen decrease in the linear region was between 1.7 and 2.8 % per minute. This would indicate the oxygen should be depleted between 7 and 12 minutes if oxygen levels started at atmospheric 20.9%. However as can be seen in the final column this usually takes slightly longer due to the initial and final transition zones. For the substrate aerated through pouring, oxygen dropped below 2.0% between 11 and 18 minutes and between 7 and 11 minutes for substrate aerated through mixing.

Oxygen Sensor depth (cm)	Average Temperature (C)	Times Tube was flipped	Steady State Oxygen Level (%)	Rate of Oxygen % decrease (-%/min)	Time at which Oxygen Dropped Below 2.0% (min)
15	29	0	1.8	2.1	18
20	29	0	0.8	2.3	Na
25	29	0	0.4	2.0	15
30	29	0	0.7	2.3	Na
30	31	0	0.6	2.2	11
40	31	0	0.5	2.1	10
46	27	0	0.5	1.9	12
17	32	1	0.8	2.2	Na
22	28	2	0.6	1.7	11
23	29	1	0.8	2.3	Br
25	36	1	0.8	2.2	9
27	32	1	0.5	2.5	Na
32	28	2	Br	BR	Br
35	36	1	0.5	2.7	8
35	31	1	0.7	2.8	7

Table 2. The parameters and results for the final experiments are listed above. Br indicates the measurement device broke during an experiment, Na indicates the value could not be computed due to an error.

Visually observing the results as depicted in figure 7, it is difficult to spot trends in the data. When looking at the rate of oxygen decrease versus depth there appears to be almost no correlation for the experiments aerated through pouring. For the experiments aerated through mixing, there is a slight indication that the rate of O_2% decrease increases with depth. When placing a linear fit to this data the slope is slightly positive 4.1 +/- 4.1 (O_2%/min)/cm, however the 95% uncertainty is equal to the slope, meaning a clear positive correlation cannot be drawn. When comparing experiments with different modes of aeration there does not appear to be a

significant difference in rate of O_2% decrease. Ignoring depth, experiments aerated through pouring had an average rate of O_2% decrease of 2.13 +/-0.15 %/min, and experiments aerated through flipping had an average rate of O_2% decrease of 2.34 +/- 33 %/min. Note the large overlap in uncertainty.

When looking at the time at which oxygen dropped below 2.0% versus depth there appears to be a clearer trend in the data. A linear fit was applied to both the pouring and flipping experimental groups, the slope of these fits where -12 +/-15 and -14 +/- 21 s/cm respectively. In both cases the uncertainty was greater than the slope, meaning a statistically significant conclusion could not be drawn with regard to the nature of the slope, even though the general trend appears to be negative. The average time at which oxygen dropped below 2.0% was 13.4 +/- 3.8 and 8.9 +/-2.7 min for the pouring and flipping experiments respectively. While there appears to be a more significant difference in these averages, the level of uncertainty overlap is still quite high, and a statistically significant conclusion cannot be made.

Based on these measurements, it appears there is no strong correlation between depth and the time at which conditions become unfavorable for depths between 15 and 45 cm. It is possible that at these depths the amount of oxygen diffusing from the surface through the substrate is very small. In this case the rate of oxygen decrease is dependent just on the metabolic rate of the organism, which should be mostly independent of depth. This speculation is supported by the low steady state of oxygen levels measured. It should be noted that the substrate used would greatly affect this. More porous and dryer substrate would allow for higher levels of oxygen diffusion.
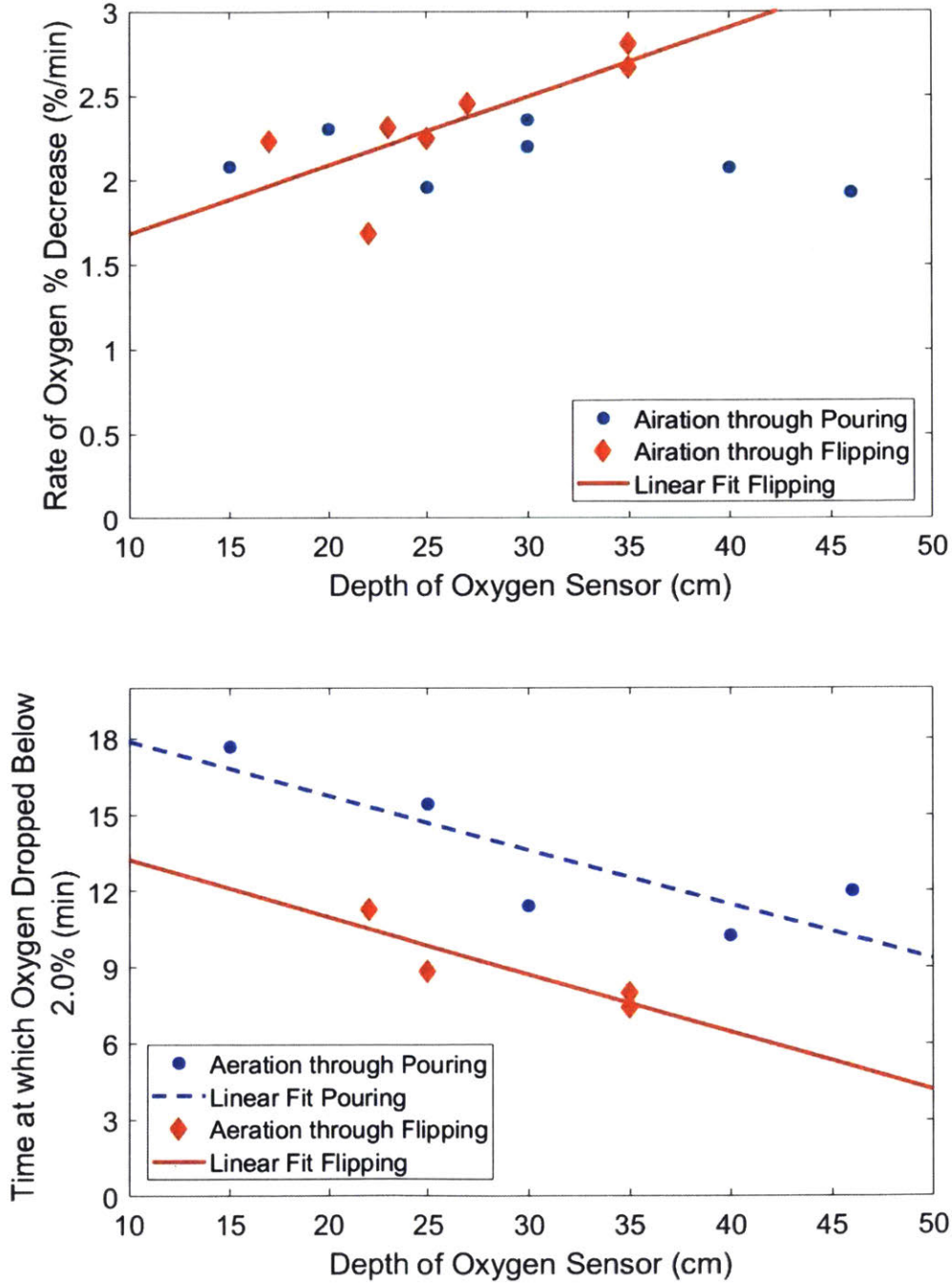
Fig 7. A visual representation of the results. The top graph is the rate of O_2 decrease versus the depth of the oxygen sensor. The bottom graph is the time at which O_2 dropped below 2.0% versus the depth of the oxygen sensor. Diamonds indicate the flipping was the method of mixing. Lines are linear interpolations of the data. None of the trends indicated by the interpolants where statistically significant.

Observations were made throughout the experiments and provided insight to a degree almost greater than the measurements recorded. For most experiments shortly after $O_2\%$ dropped below 2.0% larvae were seen traveling to the surface of the substrate. Then about 5-10 minutes after the steady state was reached larvae were observed congregating at the top of the substrate such that the top 2-4 cm where composed almost completely of larvae. This is depicted in figure 8. At this point the experiments were usually ended as it was clear conditions inside the tube had become unfavorable. Larvae that were particularly deep in the tube tended to become listless and stop moving rather than try to make it to the surface. Both of these behaviors are stressful for the BSFs larvae and indicate poor environmental conditions.
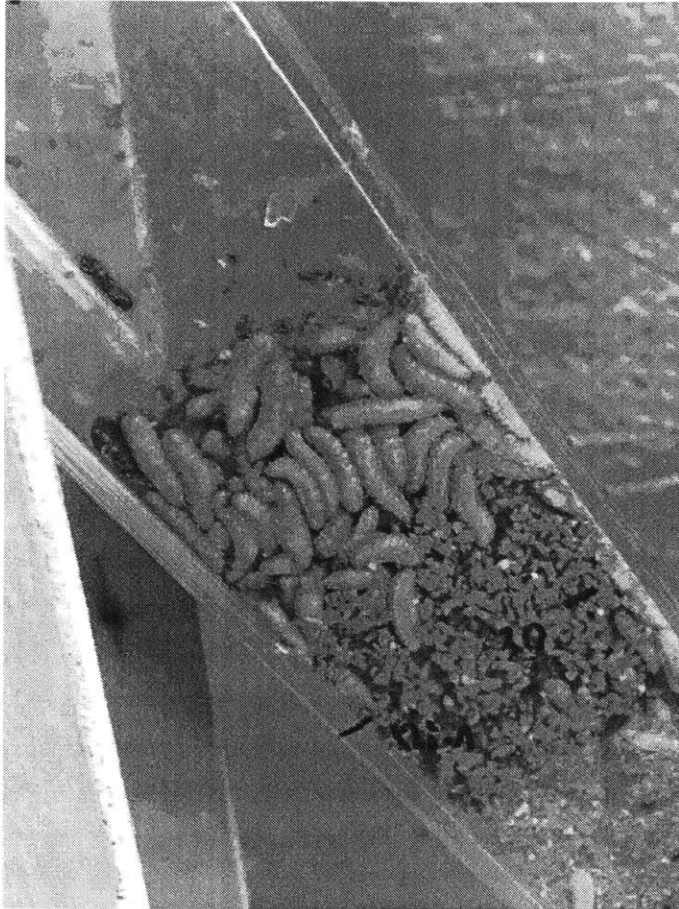
Figure 8. Larvae congregating at the surface of the substrate during an experiment. This was a clear observation that conditions in the substrate where unfavorable. This phenomena was observed in multiple trials.

Keeping all environmental variables constant throughout experimental trials was not achieved, and this led to a high level of variation and uncertainty in the results. However, when using observations in addition to the results, it becomes clear that conditions for black soldier fly growth in the substrate used became unfavorable in all cases under 30 minutes, regardless of changes in environmental variables. Under the worst conditions it appeared conditions could become unfavorable in as little as 5-10 minutes. After a depth of 15 cm it appears the rate at

which conditions become unfavorable from oxygen depletion was minimally affected by depth, but this cannot be definitively concluded due to the variability in the experimental conditions.

These results do not support the feasibility of using a screw conveyor. Based on these results, in order to be sure that the lower substrate depth would not become anaerobic, a screw growing BSF larvae would have to turn every 5-10 minutes. While the energy cost of doing this would not be prohibitively high, from a practical standpoint this would be difficult. This would be almost a constant disturbance to fly larvae. Also it leaves very little leeway for failure if the screw conveyor stopped working for some reason. If the screw conveyor were to operate in a standard fashion such that there is only mass flow in one direction, the screw conveyor itself would have to be absurdly long if the BSF larvae were to spend one to three weeks maturing in it.

It should be noted that there were many elements of this experiment that were on the conservative side in terms of the experimental conditions. The tube restricted airflow over the surface of the substrate. The substrate was on the moister side and had a high average caloric energy level. The density at which the BSF larvae where grown was also relatively high. All of these conditions can cause the substrate to become anaerobic more quickly.

5. Conclusion

This research proposed the use of screw conveyors as a method of continuously growing BSF larvae. In order to evaluate the feasibility of this system the energy costs associated with using screw conveyors were predicted. Physical Experiments were also done to predict the effectiveness of mixing in a screw conveyor to aerate the substrate and allow BSF to live at depth below 10 cm.

Based on the calculations done in this study, energy costs would likely be small, if not trivial, on per unit mass produced basis. Using the equations in the KWS engineering guide and information given by Enviroflight on BSF production, this study predicted energy cost on the order of 1 cent or less per pound BSF produced. Energy cost increased with diameter and revolution per hour, the maximum values were 36" diameter and four revolutions per hour. Even with these values, predicted energy costs were minimal.

It is common knowledge in the industry that BSF larvae cannot be grown in substrate deeper than 10 cm due to the development of anaerobic combinations. This study attempted to quantify this phenomena and test the effects mixing might have in oxygenating substrate and allowing BSF to live deeper in their substrate thereby increasing space efficiency.

Based on the results and observation of the experiments conducted, oxygen levels decrease too rapidly for mixing to be a viable aeration method. The substrate in all the final experiments at depths below 15 cm became anaerobic in less than 30 minutes and in many cases less than 10. This had a clear negative effect on the larvae which either migrated to the surface or became listless.

There were many variables in these experiments and many of these variables were set to the conservative side. It is possible under certain conditions results could have been more favorable and oxygen levels could have decreased slower and stayed above the anaerobic zone. The depth at which BSF larvae can be grown is important regardless of the growing method and deserves further study. Future research should look further into the effects of moisture and porousness of the substrate on oxygen depletions as well as test out different types of substrate such as food waste or brewers grain. The density at which BSF larvae are grown and the age of the BSF larvae are also important variables that likely have a considerable effect on the rate of

oxygen depletion and warrant further study. It is also possible that airflow over the substrate surface could significantly increase the diffusion of oxygen through the substrate, and future research should consider looking into this. With improved conditions, the time at which the substrate becomes anaerobic could be long enough to make using screw conveyors possible. However, the results of this study does not support its feasibility.

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