

EVALUATION OF THE ECONOMIC, SOCIAL, AND BIOLOGICAL  
FEASIBILITY OF BIOCONVERTING FOOD WASTES WITH  
THE BLACK SOLDIER FLY (*Hermetia illucens*)

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Food wastes in the waste stream is becoming an important aspect of integrated waste management systems. Current efforts are composting and animal feeding. However, these food waste disposal practices rely on slow thermodynamic processes of composting or finding farmers with domestic animals capable of consuming the food wastes. Bioconversion, a potential alternative, is a waste management practice that converts food waste to insect larval biomass and organic residue. This project uses a native and common non-pest insect in Texas, the black soldier, which processes large quantities of food wastes, animal wastes and sewage in the larval stage. The goal of this research is to facilitate the identification and development of the practical parameters of bioconversion methods. Three major factors were selected to evaluate a bioconversion system: (1) the biological constraints on the species; (2) the economic costs and benefits for the local community; (3) the perception of and interaction between the public and management agencies. Results indicate that bioconversion is feasible on all levels. Larvae tolerate and consume food waste reducing the volume by over half. The economical benefits are reduced collection costs and profit from the sale of pupae as a feedstuff. Social acceptance is possible, but requires education of the public, specifically targeting school children.

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## CHAPTER 1

### INTRODUCTION

Conventional disposal of food wastes, into sanitary landfills and sewers, can lead to both local and global problems (Enger 2000). The primary concern of all landfills is life expiration, which requires a new site to be located, bought, permitted and constructed, all together a very expensive process (Bauhu and Meiwes 1994). Furthermore, potential odors from landfills and wastewater treatment facilities affect local residents and businesses. Food wastes rich in oil and grease washed down sinks obstruct sewer pipes, while those disposed in routine garbage collection create fouling problems for recyclables. Globally, organic matter anaerobically decomposing in landfills produces methane gas, a greenhouse gas associated with global warming, and landfill leachate, which may pollute groundwater over long periods of time (Goudie 2000; Read et al. 2001).

Food wastes in the waste stream is becoming an important aspect of integrated waste management (IWM) systems. Current IWM system efforts are usually oriented around composting vegetative yard wastes (e.g. grass clippings, tree branches) (Bauhus and Meiwes 1994), animal feeding (Agunwamba et al. 1998), and restricting grease disposal from restaurant businesses into sewer systems. However, these food waste disposal practices rely on slow thermodynamic processes of composting or finding farmers with domestic animals capable of consuming the food

wastes. Furthermore, not all food wastes can be composted or fed to animals, and a portion of food wastes are still buried in the landfill.

Bioconversion, a potential alternative, is a waste management practice that converts food waste to insect larval biomass and organic residue. Many different organisms may carry out the process of bioconversion with a variety of food types. This project will use a native and common non-pest insect in Texas, the black soldier, which process large quantities of food wastes, animal wastes and sewage in the larval stages (Olivier 2000; Sheppard et al. 1995). In order to evaluate a food waste bioconversion system sufficiently, three major factors must be determined: (1) the biological constraints on the species; (2) the economic costs and benefits for the local community; (3) the perception of and interaction between the public and management agencies.

The City of Denton had approximately 82,976 residents in 2001 and expects a 89.83% growth by 2025, making the population 157,654 residents (NCTCOG 2001). With this growing population, Denton generates a considerable amount of solid waste, including food wastes. One noteworthy contributor to the waste stream is the University of North Texas, with a population of approximately 31,000 students. Approximately 1.2 million meals are served at the University of North Texas per year, equating to about 1.1 million kg of food per year. Disposal rates for the Denton Municipal Landfill are one of the highest in the state, at approximately 3.4 kg/person/day in 1999, compared with a nationwide per

capita daily average of 2.0 kg of municipal solid waste (Brady 2000). Currently, food wastes—along with most solid waste—is buried in Denton Landfill and a portion is disposed into the sewer system, through sinks and garbage disposals. These wastes often contain oils and grease that restrict flow in the sanitary sewer pipes, creating a burden on the Wastewater Treatment Plant. The pipes are flushed each year at an expense to the City of Denton of approximately \$250,000 per year (Coulter 2002). There are a few recycling programs offered by the city, the University of North Texas, and Texas Women's University, but none address food wastes.

Using the black soldier fly as the species of interest in this dissertation, the bioconversion process will be biologically characterized, economically analyzed and socially developed during 2002 to 2004. The goal of this research is to facilitate the identification and development of the practical parameters of bioconversion methods, incorporating biologic, economic, and social facets, based on food waste management for the black soldier fly larvae in cafeteria-sized operations.

The project is divided into three categories: biological analysis, social analysis, and economic analysis. Specific research objectives for this project are:

Economic Analysis:

- Analyze potential cost savings for cafeteria-sized bioconversion

- Develop a set of guidelines and criteria important in designing and managing bioconversion system for cafeteria-size utilization potential

#### Social Analysis:

- Investigate factors determining the acceptance of insects
- Research directions for community outreach by creating educational material including a children's book and 5<sup>th</sup> grade curriculum
- Develop a set of guidelines and criteria important in designing and managing bioconversion system for cafeteria-size utilization potential

#### Biological Analysis:

- Characterize prepupae growth and development with respect to artificial diets
- Characterize food waste reduction with respect to diet.
- Using result of this study and evaluation of the literature, determine optimum conditions for bioconversion system
- Develop a set of guidelines and criteria important in designing and managing bioconversion system for cafeteria-size utilization potential

## CHAPTER 2

### LITERATURE SURVEY

#### History of Waste

People have always created garbage. The earliest humans were nomadic, frequently moving from place to place leaving behind their garbage (Carless 1992). As evolution from a transient life-style to a more sedentary one took place, wastes began to accumulate (Kimball 1992). Originally, garbage was treated as an aesthetic issue, it looked repulsive, was malodorous, and attracted vermin (Kimball 1992). As people established permanent settlement (Kimball 1992), garbage began to cover their floors, at which time they covered the garbage with a layer of dirt or clay and started again on a clean floor (Carless 1992). At one point household garbage and debris were thrown into the streets where pigs or other animals ate anything edible and scavengers and scrap merchants took their share (Carless 1992). The streets became filthy and people began to discover a host of health problems associated with their wastes, eventually prompting people to take action (Carless 1992; Kimball 1992). Procedures for collecting and removing refuse from populated areas were established, but little thought was given to the ultimate disposal of solid waste (Kimball 1992). It was Athens in 500 B.C. that organized the first municipal dump in the western world (Kimball 1992; League of Women Voters 1993). Waste was required to be disposed of at least one mile from city walls (League of Women Voters 1993). Yet, sheer quantity of waste

plagued the Western world despite management procedures. In 1400, waste from Paris, France was piled so high outside the city gates it interfered with the city's defenses (Kimball 1992). And in 1415, during a Portuguese attack on a Moroccan city, a dump made history as it was captured, when mistaken for a strategic hill (Kimball 1992).

### Waste Today

Today technology and scientific innovation are progressing with exponential speed, yet along with this increase an old problem is acutely obvious: the generation of solid waste. The amount of refuse thrown away in the United States has more than doubled in 30 years, while the population has increased by only 38% (League of Women Voters 1993). Municipal solid waste (MSW) is most often broken down into its two major sources, residential and commercial. The EPA (2000) estimated residential waste to be 55 to 65 percent of total MSW generation. Commercial waste constituted between 35 to 45 percent of MSW (EPA 2000). Environmental Protection Agency studies (2000, 2002) indicate that trends in MSW generation from 1960 to 1999 are steadily increasing. This generation rate has increased since 1960, when it was 1.22 kg per person per day to 1.7 kg per person per day in 1980 and 2.0 kg per person per day in 1998 (EPA 1998, 2002). With this industrialization, waste takes the form of solids, sludges, liquids, gases, and disposal of these wastes has been conventionally carried out according to one of three basic methods:

sanitary landfill, incineration, or composting (Oweis and Khera 1998; Pavoni, Heer, Hagerty 1975).

Land disposal, in the form of landfills, surface impoundment, land application, and deep well injection are the most common form of waste management for nonhazardous and hazardous waste (Oweis and Khera 1998). Municipal landfills consisted of heterogeneous mixtures of wastes that are primarily of residential and commercial origin (Oweis and Khera 1998). Food and garden wastes, paper products, plastics and rubber, textiles, wood ashes, and the soil used to cover the material are typically found in municipal landfills (Oweis and Khera 1998). Between 1973 and 1993 the number of landfills in the United States decreased as a result of reaching capacity or failure to meet state or federal landfill design, operation, and environmental safety standards (Carless 1992; League of Women Voters 1993).

Although people have burned garbage throughout history incinerators, appearing in the late 1890s are waste-to-energy facilities, convert energy from burning garbage into steam or electricity (Carless 1992). Reductions in waste volume result from incineration, however there are costs of controlling and monitoring pollutants from air emission, disposal of incinerator ash, and the financing and siting of the facilities (League of Women Voters 1993).

Organic wastes that are not landfilled have traditionally been treated in one of two ways, composting or vermicomposting. And recently

various other ways have developed such as integrated systems and bioconversion. Composting organic wastes into organic fertilizers through thermophilic composting is used to address environmental pollution, chemical-free fertilizers, and soil improvement. In its early years, composting was not practiced to a large degree in the United States because of the relative availability of arable land and abundance of inexpensive fertilizers (Pavoni, Heer, Hagerty 1975), but given the loss of agricultural land for urban development and strict regulations on fertilizers, pesticides and other chemicals, composting has become a more common practice. Although composting provides many benefits there are problems associated with traditional thermophilic composting. The process is often long, requiring frequent turning of the material, at times requiring reduction to increase surface area (Ndegwa and Thompson 2001). In addition, nutrients may be lost during the process and the product is, by nature, heterogeneous (Ndegwa and Thompson 2001).

Vermicomposting (using earthworms to breakdown organic material) has recently become more popular. This process is a low-cost system using earthworms to consume organic material residuals reducing them into finer particles as they pass through their grinding gizzard (Ndegwa and Thompson 2001). Concurrently, the worms promote microbial activity as a result of their castings (Ndegwa and Thompson 2001). One problem with vermicomposting is that the process must be maintained below 35°C, otherwise the worms will die (Ndegwa and

Thompson 2001). At these temperatures the organic material never reaches a temperature to kill pathogens and pass EPA rules for pathogen reduction.

The drawbacks of both thermophilic composting and vermicomposting have inspired alternative methods of disposal. Integrated systems borrows attributes from both processes resulting in short stabilization time, and improved the product quality (Frederickson et al. 1997; Ndegwa and Thompson 2001) using the best attributes of multiple natural processes to management wastes.

Bioconversion is the newest method for addressing organic waste using fly larvae. Organic material is consumed by the larvae and converted to biomass and organic residue, which may be further composted.

While waste management options grow more sophisticated as a result of more diverse and plentiful wastes and new technologies (League of Women Voters 1993), all methods of waste disposal are in the final analysis landfill. Even the most sophisticated processes produce residues that require landfilling (Holmes 1983). The choice lies in selecting the level of capital cost, operating cost, pollution risk and environmental impact of the various options open to waste management agencies and private operators (Holmes 1983).

Local governments bear the primary responsibility for managing waste. Challenged by budgets, land scarcity, dense populations, large

volumes of waste, and environmental concerns government agencies are integrating solid waste management options, actively encouraging source reduction, recycling, composting, incineration, and landfilling (League of Women Voters 1993; Oweis and Khera 1998). New regulations governing waste disposal make finding a suitable site for disposal in densely populated areas more difficult (Oweis and Khera 1998). Therefore, the emphasis has moved from waste disposal to waste reduction, reuse and recycling (Oweis and Khera 1998).

### Evolution of Recycling

To address economic and environmental issues associated with MSW management, the EPA developed a solid waste management hierarchy in 1989 encouraging the country to integrate several approaches into solid waste management—source reduction, recycling and composting, incineration, and landfills (Kimball 1992; League of Women Voters 1993). No approach to MSW management is more widely praised and less widely practiced than the simple idea of producing less garbage in the first place. The idea depends on a fundamental social and cultural change in the consumptive and convenience oriented behavior and attitudes of consumers, manufacturers, and policy makers.

The early twentieth century was a time of recycling before there was even an economic market. Born out of necessity in the early 1920s seventy percent of the nation's cities ran programs to recycle select materials (League of Women Voters 1993), and during World War II, 25

percent of the waste stream was reused (Carless 1992; Kimball 1992, League of Women Voters 1993). Yet only a few decades later, the nation turned sharply. The 1950s and 1960s glamorized the highly successful disposable industry, selling the idea that single-use, throw-away items were absolute necessities of a modern life-style (Kimball 1992). The realization that the concept of “unlimited” might be unfounded began to dawn on U.S. citizens in the late 1960s (Carless 1992; Kimball 1992). Pictures of Earth from space, showing our planet sitting alone, an undeniable closed and finite system, may have afforded the public a new perspective on planetary limits (Kimball 1992). During this time, toxins in land, air, and water were also discovered and in concert with the publication of Rachel Carson’s *Silent Spring* in 1962, the idea that our species may negatively impact life on Earth became a reality.

It was the 1960s that saw agency focus move to improving management techniques of solid waste (Pavoni, Heer, and Hagerty 1975). In 1970 the EPA was created and its Office of Solid Waste was formed specifically to examine the problems caused by the generation and disposal of wastes (Kimball 1992). In 1973 with the advent of the energy crisis, and the passage of the Resource Conservation and Recovery Act (RCRA) in 1976 which mandated that dumps be replaced with regulated and closely monitored landfill facilities, Americans began to look at their waste disposal habits and to focus on energy recovery systems (Kimball 1992, Pavoni, Heer, Hagerty 1975). The following decade saw recycling

by individual and some business occurred on a limited but profitable basis (Kimball 1992). In 1980s the infamous wandering “Garbage Barge” that sailed up and down the Atlantic looking for a location to dispose its trash, coupled with rising tipping fees and corpses of marine mammals washing up on beaches, a sense of urgency was created with regard to waste disposal (Kimball 1992). The idea that “there is no such place as away” finally became a reality to most Americans (Kimball 1992). However, while spatial limits were slowly being understood, beliefs that time and technology would save the day continued to plague active and wide participation in recycling. Recycling business has evolved into a major industry, faced with the economics of big business (Kimball 1992). Many small recyclers have failed because they could not deal with the financial realities (Kimball 1992). However, the economics of recycling remain the same: The dollar cost of recycling far outweighs the dollar value of the recyclables (Kimball 1992). Considerable debate exists over the economic feasibility of further recycling and the development of markets for recyclable products (League of Women Voters 1993). It may take up to five times the amount of money a recyclables product is worth to collect, process, and transport it to a buyer (Kimball 1992). Therefore, the recycling market is driven by consumer demand, not profit (Kimball 1992). Today recycling and composting are household and community activities often a result of environmental concerns. Reusing materials such as aluminum, paper, glass and plastics saves energy costs, spares

environmental impacts and reduces the extraction and processing of virgin materials (League of Women Voters 1993). Advocates of recycling argue that the steady supply of recyclable but sporadic demand require an evaluation on more than cost and sales (League of Women Voters 1993). Environmental economists point out that in sustainable economic systems (one based on the real costs to the environment resulting from the transportation and production of goods and materials) recycling would be financially cost effective (Kimball 1992; League of Women Voters 1993) and garbage fees should reflect the full cost of waste management (League of Women Voters 1993).

Problems facing recycling efforts are numerous, but changing the public's habits may be one of the most difficult (Carless 1992). Recycling doesn't come naturally to many industrialized nations because of the buy—use—dispose habits that are so well entrenched. In support, Oweis and Khera (1998) found that the more prosperous a country, the larger the proportion of salvageable materials in the waste stream. Although public apathy is an obstacle in initiating and sustaining recycling programs it is not impossible because recycling and waste disposal in general have been around for centuries and are in a continuing state of evolution. With the initiation of public education programs people are beginning to become less concerned with the money they can earn from their trash (Kimball 1992). Instead recycling is focused on a cleaner, greener Earth, with more trees, cleaner water, and fresher air (Kimball 1992). The

emphasis has changed from monetary incentives to environmental ones (Kimball 1992). Current recycling collection methods include curbside programs, drop-off sites, buy-back centers and materials recovery facilities (Carless 1992).

### Landfill Problems

In the past landfills were created to protect the environment and society, however, new problems have arisen. Aside from potential health hazards, concerns include fire and explosions, vegetation damage, unpleasant odors, landfill settlement, ground water pollution, air pollution and global warming (El-Fadel, Findikakis, Leckie 1997). Gas and leachate generation resulting from microbial decomposition, climatic conditions, refuse characteristics and landfilling operations are also inevitable consequences of the MSW disposal.

A complex sequence of biological, chemical, and physical events occur when solid waste is placed in a landfill, resulting in gaseous and liquid emissions (Reinhart 1993). Leachate is produced as water percolates through the solid waste, leaching soluble components and degradation products from the waste (Reinhart 1993). Landfill gas, on the other hand, is generated during stabilization of solid waste organic fractions (Reinhart 1993). Serious environmental concerns are ubiquitous as gas and leachate migrate away from landfill boundaries and into surrounding areas.

Solid waste composition is one component of understanding and managing environmental impacts of landfilling. Understanding the composition is often confined to a region and may vary considerably from country to country because composition varies with socio-economic conditions, location, season, waste collection and disposal methods, sampling and sorting procedures (El-Fadel, Findikakis, Leckie 1997, Oweis and Khera 1998). For example, food waste percent dry weight ranges between 20 to 50 in the European community and only 6 to 18 in the United States (El-Fadel, Findikakis, Leckie 1997). Cultural habits are also a key factor in the composition of waste as the “disposable attitude” generates more and varied waste.

Landfill gas, rich in methane, is a liability due to its flammability and tendency to migrate away from landfill boundaries. Numerous incidents of fires and explosions have been reported in the literature both at and away from landfills (El-Fadel, Findikakis, Leckie 1997). It is estimated that methane contributes approximately 18% towards total global warming (Church and Shepherd 1989). This is approximately 500 million tons per year of which 40 to 75 million tons are attributed to emissions from landfills. The rate of gas production is a function of refuse composition, climate, moisture content, particle size and compaction, nutrient availability and buffering capacity (Reinhart 1993). Reinhart (1993) reports that landfill gas is typically 40 to 60 percent methane, with carbon dioxide

and trace gases such as hydrogen sulfide, water vapor, hydrogen and various volatile organic compounds comprising the balance.

Landfill leachate has been associated with the contamination of aquifers underlying landfills (El-Fadel, Findikakis, Leckie 1997). There is a long-term potential for production of contaminated gas and leachate, to which the U.S. federal landfill regulations respond with monitoring of groundwater and landfill gas for 30 years after a landfill closure (Reinhart 1993).

The design and selection of solid waste pretreatment techniques is affected by the composition of the waste stream and economics. Waste generation is the primary management action that affects waste treatment. The minimization of waste affects the pretreatment of the waste and the disposal, whether landfilling or incineration.

Bioconversion is not a source reduction management action, but may be considered a pretreatment technique. A pretreatment technique is any process that alters the composition or other characteristics of the waste stream as generated prior to landfilling (Komilis, Ham, Stegmann 1999). Traditionally, these solid waste techniques were mechanical, thermal and biological and often used in combination in order to recover resources, produce energy, and/or minimize landfilling (Komilis, Ham, Stegmann 1999). With the discovery of environmental impacts from landfills such as gas and leachate generation several pretreatment techniques can be used to control landfill behavior.

Thermal destruction and resource recovery are gaining favor as a means of reducing the volume of municipal waste (Oweis and Khera 1998). Municipal sludges are generated from the treatment of both potable water and wastewater (Oweis and Khera 1998). Approximately 25 to 40% of MSW may be decomposed given favorable conditions (Oweis and Khera 1998). The rate of decomposition is influenced by the content of refuse, ambient temperature, oxygen supply, and water content (Oweis and Khera 1998). Heat from aerobic decomposition the initial ambient temperature and peak temperature of 71°C can occur in a few days to weeks after coverage. These high temperatures may cause combustion of dry waste, resulting in fires (Oweis and Khera 1998).

#### Study Area

In July 2002 the Institute of Applied Sciences at the University of North Texas received a grant from the City of Denton's Wastewater Division. The funding was used to implement a pilot food waste collection and bioconversion program at the University of North Texas. A food waste management initiative was developed to capitalize on shared resources of multiple participants and to integrate academics into practical, local, and economic resource recovery opportunities. The pilot program was to test the biological, economic, and social, feasibility of bioconverting food wastes with the black soldier fly (*Hermetia illucens*) by targeting 1 of the 5 residence hall cafeterias on campus.

The City of Denton, Texas is located north of Dallas in Denton County covering 62 square miles and has a population of about 87,227 (Annual Report 2002). Denton's population is expected to reach 106,025 by the year 2006 (Annual Report 2002). Denton is a bedroom community of Dallas and home to two universities, University of North Texas (31,000) and Texas Women's University (9,461). In the last few years the City of Denton has experienced an influx of social and economic development, and hence of inhabitants.

Commercial and residential refuse service in Denton is performed by the Solid Waste Department and consists of collection, recycling, and comprehensive landfill operations. The department currently services about 21,000 residential accounts, including all single family houses, duplex and triplex residences in the city limits (Personal communication with Mike Fogle 2002). The Solid Waste Department services about 2,500 commercial accounts, which include industries, commercial businesses including several restaurants, and institutions such as hospitals (Personal communication with Mike Fogle 2002). Both the Residential and Commercial Solid Waste Divisions are entirely fee-for-service based.

The Residential Solid Waste Division provides a bagged collection service twice per week and a containerized collection service, using a roll-out cart, once per week in designated areas of the City. Bagged collection rates are \$17.40 facility charge and \$0.10 state surcharge per 30 day period (City of Denton 2002). Containerized collection rates depend on the

container size. A 64-gallon container is billed at \$13.00 facility charge and \$0.10 state surcharge per 30 day period (City of Denton 2002). A 96-gallon container is billed at a \$15.00 facility charge and \$0.10 state surcharge per 30 day period (City of Denton 2002).

The Commercial Solid Waste Division provides containerized service for Denton businesses, industries, and institutions, which do not receive residential service. The containers are available in a variety of sizes and styles. Deposits are required for both regularly scheduled service and all temporary container service. The division offers front and side load containers and roll-off trucks. Front and side load container contents are collected once per week in accordance with the State of Texas Health and Safety Code requiring putrescible waste collection at least once per week. Roll-off containers are required to be collected once per month. Commercial collection rates are billed per 30 day period. The front and side load containers are billed based on size: 3 cubic yard container \$47.95 (front) \$51.54 (side), 4 cubic yard container \$55.89(front) \$60.09 (side), 6 cubic yard container \$71.79, 8 cubic yard container \$86.96 (City of Denton 2002). Commercial open top roll-off service is billed for month rental and pickup service at 30 cubic yard container \$88.90 (rental) \$275.98 (pickup) and 40 cubic yard container \$100.00 (rental) \$357.24 (pickup) (City of Denton 2002).

Yardwaste and brush are also collected by the Solid Waste Department once a week for both residential and commercial customers at

no additional charge. The Solid Waste Department chips the yardwaste, which is combined with activated biosolids from the Pecan Creek Water Reclamation Plant, and sold by the Water Utilities Beneficial Reuse Division as a soil conditioning and compost product called Dyno Dirt. Approximately 11,000 tons per year of yardwaste and brush are diverted from the landfill, which is about 10% of the total yearly solid waste collected (Personal communication with Mike Fogle 2002). Although participation percentages were not available, the participation is predominately from the residential sector (Personal communication with Mike Fogle 2002).

In addition to yardwaste Denton has several ways to participate in recycling efforts. There are six main drop-off locations around the City, including the City Landfill, which accept aluminum cans, steel and tin cans, office/school paper, newspaper, magazines, cardboard, glass, and plastic. Two addition drop-off locations accept newspaper, office paper, and magazines. Weekly curbside recycling services began November 4, 2002, by Trinity Waste Services and accepts entirely commingled materials, including aluminum, steel, and tin cans, all glass containers, all plastic containers, newspaper, magazines, all papers, cardboard, and chipboard.

Once wastes are collected, the refuse trucks (fleet of 26) haul the waste to the City Landfill located at 1100 S. Mayhill Road (Personal communication with Mike Fogle 2002). This facility is a Type I landfill

(waste deposited must be compacted and covered at least daily) for municipal solid waste and Class 2 and 3 industrial waste and has been operated by the City since 1984 (TNRCC 1997). Denton's landfill receives approximately 450 tons/day and received over 107,000 tons of refuse 2002 (Personal communication with Mike Fogle 2003). The landfill site is approximately 243 acres of which 152 acres is designated for waste burial and the remaining is green buffer space. There are currently 15 cells, approximately 9 to 10 acres each for waste burial (Personal communication with Mike Fogle 2003). Each cell area is excavated, double lined (as per Subtitle D regulations), and a leachate collection systems installed prior to waste placement. The cost varies for each cell due to each area's need for additional infrastructure. The City reports a projected lifetime of 27 years for the Denton's City Landfill (Personal communication with Mike Fogle 2003). This estimate is dependent upon the growth of the City and the waste increase that may result.

### Bioconversion Background

Bioconversion is a waste management practice that converts food waste to insect larval biomass and organic residue. Many different organisms may carry out the process of bioconversion with a variety of food types. The dissertation project uses a native and common non-pest insect in Texas, the black soldier fly (*Hermetia illucens*), which can process large quantities of food wastes, animal wastes and sewage in the larval stage. (Olivier 2000; Sheppard et al. 1995).

The research provides alternative methods that are an improvement over current practices for several reasons. Bioconversion is a practice of recovering resources while simultaneously limiting the amount of organic material affecting landfill behavior. The benefits of bioconversion including:

- Diversion of food wastes from the Denton Municipal Landfill providing greater disposal capacity
- Reducing potential landfill odor problems
- Reducing fouling problem for recyclables
- Reducing obstructed sewer pipes
- Reduces methane gas production from landfills as a result of anaerobic breakdown of organic materials (Goudie 2000)
- Reduces the energy costs associated with transportation of food wastes
- Benefits for educational institutions from elementary to college by providing information to create a practical as well as educational tool, incorporating the fields of ecology, biology, economics and an essential lesson in sustainability

The biological process of bioconversion occurs naturally and commonly in backyards. Studying it on a larger scale is a first step in determining the feasibility of making this method of food wastes disposal

available and manageable by a private entity or municipality. A similar project at the University of Georgia at Tifton uses black soldier fly larvae to bioconvert chicken manure (Sheppard 1983). A portion of the resulting larvae is then fed to chickens, while the rest are allowed to metamorphose into adults to continue the cycle. There has been no research evaluating the effectiveness of black soldier fly larvae to bioconvert food waste in contained systems. The successful completion of this dissertation will identify and develop bioconversion methods based on food waste management for black soldier flies in contained operations.

In bioconversion the consumption of food waste and the healthy development of larvae rely on environmental factors that influence the physiology of the species and diet. Temperature, moisture content, density, physical and chemical properties of the medium, and competition are important variables; the relative influence of each factor can change given certain contexts and situations (Barnard and Harms 1992; Farkas et al. 1998; Jackson et al. 1998). While there has been general acceptance that many flies will consume of a wide variety of diets and previous studies indicate that black soldier fly larvae will feed on poultry and cattle manure (Booram et al. n.d.; Sheppard 1983; Shepard 1995; Tingle et al. 1975), no studies exist using artificial and food waste diets.

Little resources are wasted in the bioconversion process. The larvae are self-harvesting and the literature indicates that the prepupae are an excellent source of feedstuff for fish, swine and chicken or useful

for biopharmaceutical purposes (Booram et al. n.d.; Bondari et al. 1981; Hale 1973; Newton et al. 1977; Olivier 2000). Hence, there may be marketable uses of the larval byproduct for capitalization by commercial interests (Bondari 1981). Bioconversion also complements other recycling possibilities, such as a Materials Recovery Facility (MRF) where recyclable resources are sorted and recovered from a commingled waste stream since black soldier fly larvae may serve to decontaminate recovered recyclable items, such as glass and tin.

### Black Soldier Fly

The black soldier fly (*Hermetia illucens*) is a large stratiomyid fly found world wide, but it is believed to have originated in the Americas (Callan 1973; Kovac and Rozkosny 1995). It often occurs in moist tropical and subtropical regions throughout the world (James 1935). Although primarily adapted to these regions, it can tolerate wide extremes in temperature (Callan 1973) except when ovipositing. *H. illucens* is often mistaken for a wasp; however it does not bite or sting (Drees 1998). The adult fly measures up to 20 mm in length (Callan 1973) with a cylindrical abdomen easily recognized by “windows” of translucent cuticle (Oldroyd n.d.). Adult flies vary in color from black, metallic blue, green or purple, to brightly colored black and yellow patterns (Drees 1998).

Adults engage in an aerial mating process and females oviposit near suitable larval medium (Sheppard et al. 1995). The medium may vary considerably as larvae have been found in decaying organic matter,

including beeswax, catsup, decaying vegetables, potatoes, and manure (Drees 1998; James 1935; Sheppard et al.; 1995; Oldroyd 1964). Newly hatched larvae are particularly beautiful with translucent bodies and a black eye spot. Watching the twists and turns of their tiny bodies as they wiggle through food can be mesmerizing. An appreciation of larval movement requires time and education to fully experience this beauty. The larvae can mature in two weeks if conditions are ideal; however, food shortages may extend this period to four months (Sheppard et al. 1995). In the prepupal stage the larvae will self-harvest or crawl out of the organic waste in search of a suitable location to pupate. Pupation usually lasts two weeks, but is highly variable (Sheppard et al. 1995). Upon metamorphosis, the adult fly lives for only a few days or weeks, and does not bite or engage in pest-like behavior. It does not seek to enter homes or restaurants, but lives its short adult life remote from humans, maturing and mating primarily in wooded areas (Sheppard and Newton 1995).

*H. illucens* are poikilotherms, as are most insects, and temperature directly affects growth and development (Gullan and Cranston 2000). Despite available food resources temperature may retard or escalate growth and development. Optimum temperatures for culturing and studying *H. illucens* range from 24 to 29.3° C (Sheppard and Newton 1995; Furman et al. 1959; Bradley and Sheppard 1983; Tingle and Mitchell 1975; Booth and Sheppard 1984). Tingle, Mitchell, and Copeland (1975) found no adult emergence when pupae were held at 7.1°C and at

12.6°C twenty-seven percent of field-collected pupae emerged, suggesting a developmental (or growth) threshold between 7.1 and 12.6°C.

The larval stage of *H. illucens* is threatened by the loss of body water in a terrestrial environment (Gullan and Cranston 2000). Moisture content of the air may potentially affect the physiology and, in turn, the development, longevity and oviposition of this insect (Gullan and Cranston 2000). Like temperature, unfavorable humidity affects growth, resulting in problems when estimating development times. Laboratory studies with *H. illucens* range from 50 to 99% relative humidity (Bradley and Sheppard 1983; Booth and Sheppard 1984; Furman et al. 1959; Tingle et al. 1975).

These insects are decomposers; in essence they are one of nature's waste management agents. The fly larvae process is recycling at its finest, making use of many available nutrients found in these waste streams (Olivier 2000). Further, the adult *H. illucens* is not a pest, and actually drives off the common housefly usually associated with wastes and health hazards (Sheppard et al. 1995; Furman 1959; Sheppard 1983; Tingle 1975).

## CHAPTER 3

### ECONOMIC CONSIDERATIONS

#### Introduction

The economic feasibility of bioconversion on a cafeteria-sized scale at the University of North Texas addresses potential cost reduction through an analysis of the rate charged by volume, the food waste portion of the waste stream, money saved by eliminating the food waste portion, costs associated with installing bioconversion (including facilities, infrastructure, equipment, collection, and education), and costs (financial, environmental, social) of landfilling and treatment by the Wastewater Treatment Plant.

The United States Environmental Protection Agency (EPA) (2002) reported that in 1999 United States residents, businesses, and institutions generated more than 230 million tons of municipal solid waste, approximately 2.09 kg of waste per person per day. Of the 230 million tons, food waste compromised 10.9%, approximately 25 million tons (EPA 2002).

With such a large market to target food waste several communities have developed unique and local solution. Described below are several communities that operate food waste composting programs. The community programs data reported have not been individually analyzed to determine accuracy. A comparison of reported data is useful only as anecdotal evidence for this project.

The City of Ottawa, Canada manages food residue from the Canadian Department of Natural Resources (NRCan) cafeteria in a small in-vessel composter at an on-site location. The program composted approximately 3120 lbs/week of food residuals recovered during food preparation and when plates are returned (plate scrapings) (Sinclair 1996). The project total net cost is \$133/ton which comprising the capital cost, operating expenses and disposal cost savings (Sinclair 1996). NRCan diverts approximately 94 tons/year with an annual disposal cost savings of \$4,648 (Sinclair 1996). This partially offsets the annual cost of \$17,127 (Sinclair 1996). However, if more facilities would send food residuals to the NRCan composting unit and contribute some financial support the total cost would be further reduced (Sinclair 1996).

In Mackinac Island, Michigan participation in composting is a result of an economic incentive because landfilling is almost three times the cost of composting (Kunzler and Roe 1995). And in Hyde Park, New York at the New York's Culinary Institute of America recycling and composting have reduced waste by 61 percent. Composting diverts about 77 tons/month of food scraps, saving the school \$39,000 in disposal fees annually (Kunzler and Roe 1995). City of San Francisco, California implemented food scrap collection programs at five schools. The four elementary schools in the program diverted a total of 1700 lbs/week of organic waste (San Francisco Recycling Program Final Report).

These are examples of food waste and organic residue diversion in peer communities across the country, but there are also initiatives here in Texas. Stuckey et al. (2000) found that approximately 25% of the wastestream in Dallas/Fort Worth Texas can be safely composted, and 15% of this amount is yardwaste. Based on local needs regional programs with various types of composting projects have arisen. However, none of these projects include food waste. Texas communities need to take these programs one step further and address food waste.

Texas relies on voluntary measures to achieve its waste reduction goals. Consequently, the recycling rates for Texas cities have been lower than the national average. According to Shirlene Sitton, the recycling coordinator for the City of Denton, Denton recycles approximately 400 tons per month and this is likely to grow as the program is established. In addition to recycling the city minimizes the amount of waste landfilled by separate collection of yard waste, composting of biosolids, recycling discarded appliances and bulky items, collection and disposal of household hazardous waste and providing waste education programs to the public. Plans are also in the works to collect and use methane gas generated by decomposing waste in the landfill as another form of resource recovery. The cost of solid waste collection and disposal is financed through monthly fees included in the utility bills for residents of the City. In the past there have been no studies conducted by the citizens or City of Denton for organic waste management, specifically food wastes.

## Current Food Waste Management

MSW characterizations analyze the quantity and composition of the waste stream, by estimating how much MSW is generated and disposed of in landfills. Waste characterizations provide valuable data for making informed waste management decisions. Waste from the commercial sector of the community, which makes up an estimated 39% of Denton's solid waste stream, was studied in 1999 to determine the composition of wastes disposed and analyze options for diversion of materials from the City Landfill. The 2002 characterization of the Municipal solid waste stream in Denton, Texas found the general composition of the local solid waste stream was not significantly different than the composition of the nation's solid waste stream (Brady 2000).

In 1997, the United States generated 217 million tons of MSW, for an average of 2.0 kg/person/day (Franklin Associates 1999). Denton disposal rates were higher than the national average, approximately 3.4 kg/person/day (Brady et al. 1999). Food waste comprised approximately 10 percent of the nation's waste stream in 1999 (Franklin Associates 1999) with similar results in Denton of approximately 12 percent (Brady et al. 1999). More specifically, food waste composed 12.16 percent of Denton's commercial waste stream by weight. Of six waste substreams identified in the study multi-family residential and restaurant substreams had 10.33 percent and 41.25 percent, respectively, of food waste by weight (Table 2-2) (Brady 2000). The restaurant substream has the greatest food waste

composition by both weight and volume. The remaining substreams do not offer as fruitful a source of food waste for bioconversion with less than 10% of the disposed tonnage food waste.

Table 3-1. Food waste percentage by weight and volume of substream's disposed tonnage (Brady 2000).

Substream	% by Weight	% by Volume
Multi-Family Residential	10	2
Industrial	2	5
Office	4	2
Restaurant	41	19
Retail	1	Negligible
Overall	12	Not available

### Food Waste Management Options

Diversion and bioconversion of food wastes from the waste stream can be accomplished in two ways, including: collection of materials separated by institutions and placed in separate compartments on collection trucks and taken to a central bioconversion facility; and collection of material separated by institutions and placed in an onsite bioconversion facility.

The central collection option has several disadvantages including: storage space requirements at the landfill; separate collection schedule or trucks for food waste; maintaining a large black soldier fly colony; collection and transportation problems, the number of times material must be handled and the distance it is hauled directly impacts the economics of any program (Kunzler and Roe 1995). Institutions would have to source separate the food waste from the remaining waste stream in order for City

employees to collect and dispose of the food waste properly. This option does not provide any incentive to the institutions because they still pay collection fees. In fact, it may increase collection fees because the Solid Waste Divisions may need specialized vehicles for collecting separated food wastes. Given these problems central collection was eliminated as a viable option.

The onsite collection option is more appropriate with advantages including; reduced collection or tipping fee (Kunzler and Roe 1995) and potential end user material sold for a profit. There are also disadvantages of using this type of system which include: storage space requirements at the institution; unsuccessful handling and separation of food wastes; frequent and routine collection to avoid odor, health, and safety concerns; and contamination with foils, aluminum, and plastics (Kunzler and Roe 1995). Regulatory issues present the biggest hurdle for on-site composting or bioconversion programs. Many state Health Departments require postconsumer organics to be processed in covered or enclosed facilities. In bioconversion meat and dairy products as well as vegetative material is processed, which may create a regulatory problem as these items often attract vectors of disease. Many composting sites in the U.S. accept any food residuals, while others are only permitted for preconsumer food (Kunzler and Roe 1995).

The type of material generated at an institution may vary, however, all food wastes can potentially be accepted for bioconversion. Volume or

weight of food wastes will determine the size of bioconversion system necessary. Location and space requirements for collection bins and bioconversion equipment must be arranged at each institution. The frequency of collection may also vary given the amount generated and ambient temperatures. The food waste management system may also be based on processing the material by-products for sale to end users, or delivery of by-products to existing processors.

#### University of North Texas Materials and Cost for Onsite Collection

Typical feedstocks in composting programs are food preparation scraps (vegetable and fruit trimmings, coffee grounds, breads, etc.) and plate scrapings. Institutions such as universities have large dining facilities with central kitchens, which make large amounts of food waste collected easily.

The onsite collection and processing of food wastes at the University of North Texas requires a greenhouse and Bioconversion Laboratory, bioconversion tables, a black soldier fly colony, and additional labor. The greenhouse is necessary to sustain an adult colony, which supplies a continuous source of eggs. The Bioconversion Laboratory was built in 2002 and is 6 by 7 by 2m, but size is determined by ability to accommodate the food waste generated. Water and electrical utilities are available in the Bioconversion Laboratory and greenhouse to maintain temperatures of approximately 30°C. All internal parts and surfaces of the

bioconversion tables were constructed of PVC sheet and watertight sealant. The external constructions of the table is pressure treated wood and plastic gutters lining the long sides for prepupal collection. Total purchases were approximately \$11,149.00 (Table 3-2).

Table 3-2. West Hall Onsite Collection Pilot Project Costs.

Capitol Costs		
Bioconversion Building/Greenhouse	Greenhouse	\$4300.00
	Heat Pump	\$350.00
	Light Timer	\$54.42
Table Equipment	8ft 4x4	\$23.82
	8ft 2x4	\$84.96
	4x8ft ½-inch BC plywood	\$57.75
	Box of 25, ¼ by 2 ½ inch lag screws	\$20.80
	Box of 25, ¼ inch washers	\$5.95
	Gutter	\$100.00
	Drain spout	\$100.00
	¼ inch sheet white PVC	\$199.00
	5-gallon bucket	\$79.92
	5-gallon bucket lid	\$47.52
	10 quart plastic pail	\$2.34
	PVC cement	\$10.00
Cage Equipment	Outdoor Cage, 6 x 6x 6 ft., 18 x 14 mesh Lumite® screen	\$165.15
	Outdoor Steel Cage Frame for 6 ft. cage	\$106.50
Annual Operating and Maintenance		
	Rubber Laboratory Apron	\$8.99
	Latex gloves box of 100	\$12.95
	50 pack comfort mask	\$9.37
Monitoring Equipment	Digital thermometer	\$22.95
TOTAL EXPENSE		\$11,149.97

For alternative waste management system to be compared and evaluated, the volume of generated food waste must be quantified. While current figures are not complete, the University has records of the number,

size, and frequency of containers emptied regularly on campus (Table 3-3). The estimated total waste disposal for the university is 1006 yd<sup>3</sup>/week. With food waste comprising approximately 12% of the commercial waste stream in Denton (Brady 2000), this results in approximate 120.72 yd<sup>3</sup> of food waste generated by the University. However, the University has only five cafeterias on campus, which generate concentrated food waste. Food waste found in other dumpster around campus would be the result of individual lunches and snacks. Therefore, the 120.72 yd<sup>3</sup>/week may be overestimating the food waste and is certainly including food waste that is difficult to collect due to varied and remote locations. Due to these concerns, food waste data was confined only to the five cafeterias on campus.

Table 3-3. University of North Texas dumpster inventory, pick-up schedule, and cost (Custodial Services, University of North Texas, January 2003).

Location	Number and Size of Dumpster	Pick-up/week	Cost (\$/month)
APTS	1-3yd <sup>3</sup>	1	46.17
Art	Transition	Transition	241.30
Athletics Complex	2-6yd <sup>3</sup> 1-8yd <sup>3</sup>	2	132.80
Bruce Hall	1-8yd <sup>3</sup>	6	482.54
Bruce Hall Cafeteria	1-8yd <sup>3</sup>	5	402.10
Business Services Warehouse	1-4yd <sup>3</sup>	1	53.82
Chemistry (Masters Hall)	1-8yd <sup>3</sup>	5	402.10
Clark Hall	1-8yd <sup>3</sup>	3	241.30
Clark Hall Cafeteria	1-8yd <sup>3</sup>	5	402.10
Coliseum/Men's Gym	1-8yd <sup>3</sup>	3	241.30
College Inn	2-8yd <sup>3</sup> 1-6yd <sup>3</sup>	3	836.74

	1-4yd <sup>3</sup>		
Crumley Hall	1-6yd <sup>3</sup>	6	398.52
Facilities- Grounds Yard	4-4yd <sup>3</sup> rolling	1	215.28
Facilities-Paint Shop	1-8yd <sup>3</sup>	2	83.74
Facilities Structural Shop	1-6yd <sup>3</sup>	2	69.13
Gateway Center	1-8yd <sup>3</sup>	3	241.30
Kerr Hall	2-8yd <sup>3</sup>	6	965.08
Kerr Hall Cafeteria	2-8yd <sup>3</sup>	6	965.08
Library Annex	1-6yd <sup>3</sup>	2	132.80
Maple Hall	1-8yd <sup>3</sup>	3	241.30
Maple Hall Cafeteria	1-8yd <sup>3</sup>	5	402.10
McConnell	1-6yd <sup>3</sup>	Transition	482.54
Missile Base	1-4yd <sup>3</sup>	1	53.82
Oak Street Hall	1-6yd <sup>3</sup>	3	199.26
Physics Machine Shop	1-3yd <sup>3</sup>	1	46.17
Science Research Bldg.	1-8yd <sup>3</sup>	3	241.30
Student Health and Wellness Center	1-6yd <sup>3</sup>	4	265.66
Surplus Warehouse	1-8yd <sup>3</sup>	1	83.74
University Services Building	1-8yd <sup>3</sup>	5	402.10
University Union	1-30yd <sup>3</sup> Compactor	1	
UNT Apts.	2-6yd <sup>3</sup>	2	265.60
West Hall	3-8yd <sup>3</sup>	5	482.54
West Hall Cafeteria	1-4yd <sup>3</sup>	5	206.47
UNT Compactor (7 tons)	1-42yd <sup>3</sup>	1-2 (variable)	2206.58
TOTAL	1006yd <sup>3</sup> /week		12,132.38

Food waste composition of cafeteria refuse is assumed to be 19% by volume based on a 1999 restaurant substream study in Denton (Brady 2000). Although, 19% is greater than 12% food waste portion of the general commercial waste stream, restaurants deal with considerably more food products than automotive companies, thus increasing the

portion of food waste. Bruce, Clark, and Maple Hall cafeterias each collect approximately 40 yd<sup>3</sup>/week of refuse. This equates to approximately 7.6 yd<sup>3</sup>/week of food waste from each cafeteria. Kerr Hall cafeteria is the largest on campus and produces 96 yd<sup>3</sup>/week of refuse of which 18.24 yd<sup>3</sup>/week is food waste. West Hall cafeteria, the smallest on campus, produces 24 yd<sup>3</sup>/week of refuse of which 4.56 is food waste. These five cafeterias total 45.60 yd<sup>3</sup>/week of food waste, which could be diverted and managed on-site with bioconversion (Table 3-4). By diverting food waste weekly, each cafeteria could reduce its dumpster collection frequency by one day per week. Should all the food waste from the cafeterias be diverted the university would save \$536.29/month in collection and disposal cost. This is approximately \$4826.61 over a nine month school year period (Figure 3-1).

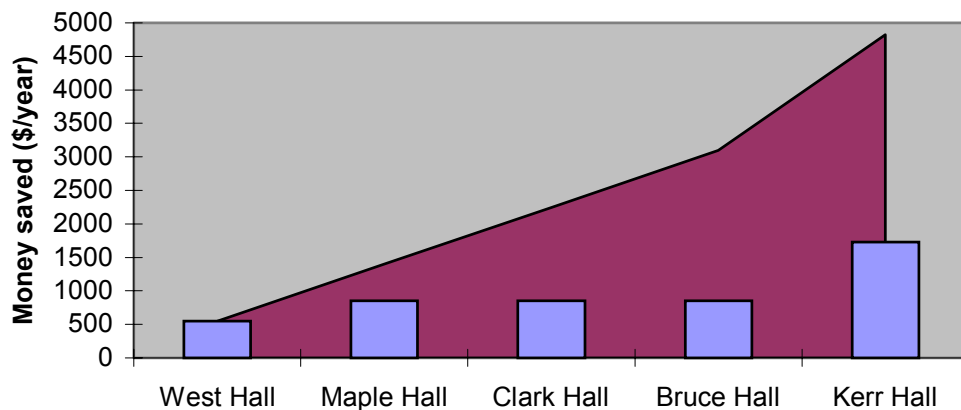
Table 3-4. University of North Texas cafeteria waste stream and cost (Custodial Services, University of North Texas, January 2003; Solid Waste, City of Denton, February 2003).

Location	Refuse (yd <sup>3</sup> /wk)	Food waste (yd <sup>3</sup> /wk)*	Adjusted Refuse (yd <sup>3</sup> /wk)	Current collection costs (\$/month)	Adjusted collection costs (\$/month)	Money saved (\$/month)	Money saved (\$/yr**)
Bruce Hall Cafeteria	40	7.6	32.4	455.16	360.78	94.38	849.42
Clark Hall Cafeteria	40	7.6	32.4	455.16	360.78	94.38	849.42
Kerr Hall Cafeteria	96	18.24	77.76	1102.46	910.32	192.14	1729.26
Maple Hall Cafeteria	40	7.6	32.4	455.16	360.78	94.38	849.42
West Hall Cafeteria	24	4.56	19.44	350.64	289.63	61.01	549.09
Total	240	45.60	194.40	2818.58	2282.29	536.29	4826.61

\*Food waste composition by volume assumed 19% based on restaurant substream study from Brady 2000.

\*\* Indicates regular school year, which is approximately nine months.

**Figure 3-1. Individual and cumulative money saved at University of North Texas cafeterias by diverting food waste.**



The pilot cafeteria, West Hall, serves on average between 600 to 900 meals each day (excluding Saturday and Sunday). Overall, approximately 1.2 million meals are served at the University per year, equating to about 2.4 million pounds per year. For this study food waste at West Hall was collected during food preparation and when plates are returned (plate scrapings). West Hall kitchen staff was supplied with two 5-gallon buckets, however to scale-up carts with wheels will allow for easy movement and transport from the kitchen to the bioconversion laboratory, located adjacent to the dormitory building. Food waste was collected periodically from the kitchen between Monday and Friday, weighed and applied to the bioconversion tables.

## Environmental Costs

The ecological systems of the planet provide a multitude of services that are critical to the healthy functioning of all life. Humans, only one of many species, directly and indirectly benefit from these services. The contributions of ecological systems to human welfare range from fossil fuels, recreation areas, food, oxygen, and water. Many ecosystem services are monetarily valued, for example the price of timber, petroleum or corn. However, a broader range of services that do not directly enter the market system are much more difficult, if not impossible, to attach a price tag. Ecosystem valuation is clearly a difficult and uncertain task, but one that has been undertaken in the last decade. "The value of the world's ecosystem services and natural capital" (Costanza et al. 1997) is a center of debate, discussion and progress in the field of ecological economics. The contentious paper presents a current economic value of 17 ecosystems services for 16 biomes, resulting in an average of US\$33 trillion per year (Costanza et al. 1997). The monetary valuation of ecosystems while uncertain and limited does at its premise acknowledge that changes in the quality or quantity of ecosystem services result in changes in human activities and the cost of these activities. Necessarily, the changes in human activities and their costs impact human welfare through established markets or non-market activities (Costanza et al. 1997).

Costanza et al. (1997) give an example of coral reefs, which provide habitat for fish. They are valued, in part, because they increase and concentrate fish stocks. A change in coral reef quality or quantity would affect commercial fisheries markets. However, a less tangible effect is the impact on recreational diving and snorkeling and biodiversity conservation. In short, the valuation of nature and ecological systems is not limited to their monetary value in current markets. In terms of the environment changes resulting from MSW management the costs and benefits may not be incurred solely by the MSW agency (e.g. Denton's Solid Waste Division), but by the local, regional, and global community. For example, clean air and water, soil formation, climate regulation, aesthetic values and good health are public goods, which do not pass through the money economy. Humans benefit from these services whether they are aware of it or not.

MSW disposal practices do affect, at some scale, the ecosystem, resulting in changes. Serious environmental concerns are ubiquitous as gas and leachate migrate away from landfill boundaries and into surrounding areas. A study conducted by Scharff et al. in 1995 concluded that most gas production in MSW landfills occurred in the initial period following disposal was caused by food and yard wastes (Komilis, Ham, Stegman 1999). Removing these readily biodegradable waste components reduces gas production during the first 10 years after disposal (Komilis, Ham, Stegman 1999). European countries are doing

just that, environmental laws in Germany allow solid waste landfilling containing less than 5% dry organic content only (Komilis, Ham, Stegman 1999).

Solid Waste Management typically employs two different units of measure for planning purposes. When converting waste volume to weight the following conversion factor was used for food waste:  $1 \text{ yd}^3 = 2000 \text{ lbs}$  (EPA 1999). The five University of North Texas cafeterias generate approximately  $45.60 \text{ yd}^3$  of food waste a week and  $2371.20 \text{ yd}^3/\text{year}$ , which is equivalent to 45.60 metric tons/week and 2371.20 metric tons/year, respectively. This is 2.2 percent of the total refuse received by the Denton Landfill in 2002. If this were diverted via bioconversion and composting from the City Landfill it would reduce the waste received from 107,000 tons/year to 104,629 tons/year. This saves the City precious landfill space that may eventually extend the life of the landfill.

### Conclusions

The specific research objectives for the economic aspect of this project are:

- Analyze potential cost savings for cafeteria-sized bioconversion.
- Develop a set of guidelines and criteria important in designing and managing bioconversion system for cafeteria-size utilization potential

Bioconversion at the cafeteria-sized scale at the University of North Texas is both feasible and potentially profitable. Initial costs of bioconversion were approximately \$11,149, but the majority of these were capital costs for equipment that may be used all five University of North Texas cafeterias (i.e. greenhouse, bioconversion laboratory). The immediate profits from bioconversion are a result of reduced disposal costs by diverting the food waste portion of the waste stream. If all five cafeteria divert food waste this results in a savings of \$536.29/month or \$4826.61/year. Another potential profit is selling the prepupae as an end-user product. Calculations provide an idea of the profits bioconversion could see. Current estimates (Sheppard and Olivier, personal communication) indicate that prepupae meal as animal feed is valued at \$550/ton. All cafeteria generate approximately 91,200lbs of food waste per week. At 54% dry matter, this results in 49,248lbs of dry food waste. With conversion rates ranging from 0.4 to 19.53, the income may range from \$55.16 to \$2693.08 per week.

Profits were calculated using the following formula:

(pounds dry food waste generated from all cafeterias/week x  
conversion rate) x \$0.28 = \$/week

Even without the potential profits from prepupae sales the profits from food waste diversion at all five cafeterias will equal the initial costs in less than three years.

There are three key guideline recommendations for initiating and managing a bioconversion system at the cafeteria-size scale. First, cafeteria food waste generation should be determined in order to provide the accurate size facilities (i.e. greenhouse, bioconversion building). Second, the system should start small and gradually scale up as with this project which began with only West Hall cafeteria's food waste. This allows for problems to be caught early and address before they are too large. Finally, commercial end-users for the prepupae should be investigated as a source of revenue as well as a disposal for large number of prepupae not used to maintain the colony.

## CHAPTER 4

### SOCIAL CONSIDERATIONS

#### Introduction

Bioconversion has two obstacles to overcome in the eyes of the public—insects and food waste. Both are generally considered disgusting and often avoided. However, both have histories not necessarily deserving of their reputation. This chapter chronicles the history influencing social attitudes toward insects. Furthermore, a historical account of insects both in their beauty and brawn is given. The assumption is that such a foundation will generate interest and, hence educate people about bioconversion. Their fear for insects is first recognized and then they can work to overcome their fears.

Food waste does not carry the same stigma as insects, generally it is not considered at all by the public, but when it is it falls under disgusting. Trash is thrown out on Monday night and picked up on Tuesday morning and that's about as much thought as it gets. This is a result of industrialization and a lifestyle built on convenience. Comparison between developing countries and the United States not only confirms this, but also uncovers the ultimate cause.

Based on the problem associated with introducing the public to bioconversion two educational tools were developed: a children's book and a curriculum for a fifth grade class.

## Bugs

"Stupid bug! You go squish now!"

—Homer Simpson

“Bugs”—insects, spiders, scorpions, and a wide variety of “creepy-crawlies”—are a misunderstood lot. Dismissed wholesale by humans by prejudice (at times well-founded) and habit, the environmental and societal roles of this group of animals are far more sublime, diverse, and incredible than we typically give them credit for or understand. It is often children who are fascinated by bugs, until they slowly subscribe to the regime of adults.

In the classification of life, most of the “creepy-crawlies” we usually call bugs are classified within the Kingdom Animalia, Phylum Arthropoda. While Kingdoms represent different groups of life (Plants, Fungi, Animals, and two bacterial Kingdoms), phyla represent fundamentally different life histories within those Kingdoms. What we call “bugs” are actually animals within different Classes of Phylum Arthropoda: Insects are of the Class Insecta (with approximately thirty-two Orders, only one of which is technically considered the Order of “bugs”), spiders and scorpions are of Class Chelicerata. To place this in a different context: brown recluse spiders are related to true bugs (like the spittlebug) in much the same way that humans are related to coral reef sponges (who have a central nerve cord similar to our spinal cord). Basically, by lumping “bugs” into one bug

group, we are ignoring the tremendous diversity of life and environmental roles that are represented by arthropods (in general) and insects (in particular).

Insects have dominated the evolutionary history of the eukaryotes and the ecology of the world's ecosystems since their emergence in the fossil record some 350 million years ago. The sheer abundance and diversity of insects is a result of this long inhabitation, short generation times, and the history of diverse and changing environmental conditions. They were alone in the skies for the first 150 million years of their existence, joined—finally--by the vertebrates starting 200 million years ago. Today there are well over 900,000 described (i.e. classified) species of insects, which make them--by far--the most speciose terrestrial eukaryotes. Many remain undescribed and many more are as of yet still unknown to science: the most credible estimates of total richness of the insects are on the order of eight to ten million species. There are approximately 400,000 described animals that are not insects, which means insects make up 90% of the diversity of the animal kingdom. In this spirit, May (1988) declared, “to a rough approximation and setting aside vertebrate chauvinism, it can be said that essentially all animals are insects.”

Of the described insects, only about 700—a mere 0.078%, less than one-tenth of one percent!—interact frequently with humans in North America (Kennedy 2001). And while insects may be revered among

biologists for their diversity and abundance, the public isn't quite as impressed. Insects loom large in the evolutionary and social history of humans, both as vectors of disease-causing pathogens and as agriculture rivals. We also tend to see insects as a representation of filth because of the feeding habits and habitat choices of a few (e.g., carrion, dark damp habitats). These issues have long histories in fostering dislike and developing phobias toward insects. More recently, the obsession with cleanliness in western culture has contributed to the rise of mindsets that include insects as pests, even though most cleaning products are aimed at killing bacteria—a whole Kingdom or two away in evolutionary terms. Hann and Ascerno (1991) conducted a survey of the Minneapolis-St. Paul metropolitan area, regarding public attitudes toward arthropods, to determine the extent of human tolerances of regional insects. As one might expect, the study found that more arthropods were tolerated in the yard than indoors (69.2% of insects were disliked or feared outside, compared with 85.9% were disliked or feared indoors) (Hahn and Ascerno 1991). Those that tolerated arthropods found either indoors or outdoors were more likely to be males with at least a high school education (Hahn and Ascerno 1991), which perhaps plays somewhat into gender-based stereotypes. Despite a dislike or fear of arthropods, only 10.3% of respondents obtained information about the arthropods they had seen (Hahn and Ascerno 1991). The results of this study compare closely with common attitudes towards “bugs”: only “dirty boys” can play with bugs, but

they should be washed thoroughly with antibacterial soap afterwards.

While some concern is appropriate, these attitudes are narrow and one-sided.

### Insect Problems

The two major diseases transmitted by insects are typhus and the plague, vectored by lice and the rat flea (*Xenopsylla cheopsis*), respectively. Both have influenced, hindered, and destroyed humans and the spread of civilization; concern for such diseases is well founded and well deserved.

Typhus is rampant under stressful, crowded human conditions, such as war and natural disasters, because regular bathing and changing clothes is impossible, which allows body lice to thrive. At times, more soldiers died of typhus than in combat, and the disease was often key in military battles, determining how many men each side had that were able to fight. Epidemics of typhus were so violent that some military campaigns suffered severely or were abandoned altogether, such as the Christian army's siege of Antioch in 1098; the second crusade, led by Louis VII of France; and Maximillian II of Germany's attempted attack on the Sultan of Hungary in 1566 (Mack and Carroll 2003).

The Bubonic Plague, caused by the bacillus bacterium *Yersinia pestis*, is a highly contagious, often fatal disease transmitted from person to person or by the bite of fleas from an infected host. Plague epidemics occurred at least since 558 AD, with the Plague of Justinian, and as

recently as 1994 in Surat, India. (Mack and Carroll 2003). Like typhus, the plague altered the outcome of wars, but it was also a catalyst for sanitation improvements in the Middle Ages. The pneumonic Plague, similar to bubonic plague, affects the lungs, causing them to fill with frothy blood, resulting in death. The first pandemic occurrence of this plague was between 1347 and 1350, which killed 25% of the population of Europe in the 14th century (around 25,000,000 people)—three times more people than died in World War II (Mack and Carroll 2003). Between the terror of the populace of what was obviously a horrible death, and the abandonment of farms and the resultant food shortages, government and business activities halted and countries came to a standstill, giving way to chaos and fatalistic views of life. When the plague came to Europe, it was accompanied by violent sneezing among the afflicted. It is rumored that the Pope passed a decree that anyone who sneezed was to be blessed by those nearby, with the hope that death might be averted. Today, most people still say "Bless you!" when someone sneezes. The plague came again between 1663 to 1668, killing millions more, with similar social results. The results of these two pandemics are still visible in the genetic code of Europeans and their descendants, who are now more resistant to the plague than other human populations. The plague isn't simply a history written into our genes, though: ground squirrels and chipmunks in the southwest United States, for example, carry the plague, and a few human cases are reported each year as a result of exposure to the rodents' fleas.

In addition to typhus and the plague there are other major diseases associated with insects. Chagas disease, which occurs in central and South America and even sometimes in south Texas, is vectored by *Triatoma* spp., a Reduviid insect often called the kissing bug. Infection is spread to humans when an infected bug deposits feces on a person's skin, usually while the person is sleeping at night. The person often accidentally rubs the feces into the bite wound, an open cut, the eyes, or mouth. Symptoms may not surface for many years when heart failure is diagnosed. Weakness and immune deficiency can also be symptoms. In fact, it is thought that Charles Darwin suffered and ultimately died from Chagas disease. He writes in *The Voyage of the Beagle* (Darwin 1836), "At night I experienced an attack (for it deserved no less a name) of the Benchuca, a species of Reduvius, the great black bug of the Pampas. It is most disgusting to feel soft wingless insects, about an inch long, crawling over one's body. Before sucking they are quite thin but afterwards they become round and bloated with blood." After the voyage, Darwin became quite reclusive. Critics have attributed this to hypochondria, but his symptoms match chronic Chagas Disease.

Malaria, a disease caused by a protist and vectored by a mosquito, is currently responsible for more human mortality than any other pathogen in the world. The complex life cycle and relationship with the mosquito makes the protist extremely difficult to eradicate and protect against, and since the visual aspect of the disease is an insect, the mosquitoes

(essentially merely the messengers) take the lion's share of the blame.

The World Health Organization estimates that 300-500 million cases occur and more than 1 million people die of malaria each year (CDC 2000).

About 1,200 cases of malaria are diagnosed in the United States each year, mostly in immigrants and travelers returning from malaria-risk areas, such as sub-Saharan Africa and the Indian subcontinent (CDC 2000). It, too, has affected human civilization, having been implicated in the fall of Rome, and the completion of the Panama Canal was only possible after the advent of malaria-preventing drugs.

Insects threaten human survival by transmitting pathogens, but also by competing directly with humans for food. They are likely our greatest competitor. Despite the massive amount of money put into pest control, insects consume 33% of human agricultural food production, and damage can be much higher in localized areas (Kennedy 2001). Of course, this number is much higher worldwide, as many developing countries are without pest control. This estimate does not include nonfood agricultural production such as fiber (e.g. cotton and wood), where insects are also primary competitors. And, much like in human populations, insects can pose a threat to agriculture through the vectoring of plant diseases. In fact, until the last century, insect-induced famine was a major limiting factor on local human population growth and expansion. The use of pesticides and insecticides is big business around the world, especially in the United States. Unfortunately, insects quickly develop resistance to insecticides.

As a result, crop losses to insects are no lower now than they were before the advent of pesticides. We are essentially in an arms race against the most serious pest species, ultimately costing millions of dollars in direct costs and innumerable amounts in social and environmental costs.

### Benefits of Insects

While the dire nature of certain insects and their associated diseases and effects cannot be discounted, there is another story of the insects, one rich with the beauty, and diversity, and beneficial aspects of these amazing critters. Like humans, insects have evolved to inhabit a variety of habitats, even what we consider to be the most inhospitable. There are insects that endure the frigid conditions of polar regions and the highest mountains, while others make their home in steamy jungles and parched deserts. Some species inhabit freshwater ponds and streams, while others swim on the surface of the ocean or live in highly saline brine water. A few can even be found in hot springs, where the water temperature reaches 60°C, or deep in caves, where they never see the light of day. Insects take advantage of all types of habitats, not with the help of tools as humans have done, but with the sheer design and operation of their tiny bodies. Insects associate themselves with plants—as leaf feeders, borers, miners, gall makers, and decomposers—and animals—as predators, parasites, blood suckers, scavengers, decomposers, and, of course, as an abundant food source for all of the Kingdoms of life.

Insects perform a vast number of important ecosystem functions: they aerate and fertilize soil; they serve as food sources and food chain links; they pollinate flowers; they help control pests and pathogens; and they decompose dead materials, helping recycle nutrients. In *The Diversity of Life* (1992), E. O. Wilson provides a succinct view on the importance of insects and arthropods in the world's ecosystems: "if [they] all were to disappear, humanity probably could not last more than a few months."

In addition to ecosystem functions in general, insects have important roles in human ecologies: they contain chemical compounds that can be used in pharmaceuticals; they play a major role in pollinating fruit trees and flower blossoms in many agricultural crops; they help control pest populations in gardens and crop fields (I put some Praying Mantises in our garden this spring!); and they are just fun to study and teach with—especially when you can gross out a parent by getting their kid to play with "bugs."

Human ecologies are not just biological—they are full of art and culture as well. As such, insects have also had a role in the artistic and spiritual development of human civilization. Human cultures have long used insects as symbols: in Asian culture the butterfly represents grace, and the bee is a symbol of hard work. Many of the earliest known religions, as well as some that are practiced today, have insects in both prominent as well as supporting roles. For example, ancient Egyptians

worshipped the scarab, a dung beetle, and the dung ball was believed to be the sun and the beetle rolled the sun across the sky (Kendall 2001). Because this activity was repeated daily, it became a holy symbol in ancient Egypt—a scarab was placed over or replaced the heart after death for those worthy of regenerations or reincarnation (Mack and Carroll 2003). (It also might suggest that the Egyptians had a good sense of humor about bodily functions, to worship an insect that basically—to put it in the terms of a modern insult—ate shit and died.) In Buddhism, the cicada is a symbol of resurrection, whereas to the Hebrews Beelzebub—literally the “Lord of the Flies”—was the devil (American Heritage Dictionary 2000).

The 19th century saw the rise of insect jewelry as fashionable. Beetles, bees, flies, butterflies, earwigs were cast as jewelry and were often very expensive. A 19th century butterfly brooch once sold for \$1,100,000 (Mack and Carroll 2003). Insect themes continue to be very common in contemporary jewelry and fabric. Insects give us luxuriant fabrics, such as silk from *Bombyx mori*, the mulberry silk moth, and also from wild silk moths and tent caterpillars (Sericulum 2002). The coccineal scale dye, made from the bodies of cochineal insects (a scale insect feeding on crops, ornamentals, cacti, and fruit and nut trees), was valued for centuries (Gibson 2003). Incas dyed ceremonial robes with this dye, and the Aztec emperor Montezuma reportedly demanded tax payments in "dye grains" or cochineal insect bodies (Mack and Carroll 2003).

Luminescent insects have also been beneficial to humans throughout history. Native American women wore lantern beetles in sacks (as a sort of flashlight) or as stickpins, and even on their toes as ground-level “headlights.” And whose American childhood was complete (at least in American nostalgia, if not in reality) without spending summer evenings chasing the fireflies across the lawn, while the adults sipped beer and watched from the porch? Fireflies have also been harnessed for early warning systems; some poisonous gases affect the amount of light that fireflies can generate, and so they were once used—like canaries in coal mines—to detect poisonous gases.

Great works of art, in literature, music, and even movies, are not without the influence of insects. From Kafka’s *The Metamorphosis* to Rimsky-Korsikov’s *Flight of the Bumblebee*, from *Charlotte’s Web* to the smoking caterpillar in *Alice in Wonderland*, from Disney’s Jiminy Cricket to Marvel Comics’ Spiderman, insects are glorified or reviled as they are used to explore, explain, or even (especially in the case of Jiminy Cricket) moralize about the human condition.

Regardless of your like or dislike at the thought of insects sharing your space, the fact is we have shared *their* space for thousands of years and will likely continue to do so for many more to come. Appreciating the benefits insects offer us, as well as being aware of potential problems, provides a more accurate and balanced portrait of insects. For the insect is a creature rich in history and meaning and should not be brushed aside

too quickly. Vladimir Nabokov's statement in *Ada* summarizes the beauty of the insect, "If I could write...I would describe, in too many words no doubt, how passionately, how incandescently, how incestuously—c'est le mot—art and science meet in an insect."

### Industrialization and Food Waste

Differences in food waste practices between the United States and less developed countries occur at several locations within the food system, including at sources, in consumption, and in disposal and/or loss of waste. Change in food systems within a country is a function of fundamental changes in family structure and workforce, globalization of markets and culture, and booms in information and biological and other technologies, which can differ markedly from country to country regardless of financial standing in the global economy. Currently, the key difference between the U.S. and developing countries is the money and time available to dedicate to waste management.

Food waste management begins with the source, food loss. In the U.S., food loss exceeds 28 percent of the available edible food supplies according to a USDA study (Mundy 2002)—a total of 96 billion pounds of edible food. The majority of these losses are fresh fruits and vegetables, accounting for 18.9 billion pounds of total losses (Mundy 2002).

Losses begin on the farm, from weather, insect, disease, or weed infestations, and continue through the processing and marketing sectors (Mundy 2002). On average, food is handled 33 times before it reaches the

consumer, and each step of the process contributes to loss due to shrinkage, bruising, wilting, bacterial degradation, microbial growth, and temperature variations (Mundy 2002). Further, some of the food that does reach foodservice establishments (restaurants, cafeterias, supermarkets, etc.) is discarded as excess. For example, in fast food restaurants, preparation waste, uneaten food, and soiled papers comprise approximately half the total waste stream (Kunzler and Roe 1995). In supermarkets, organic residues represent about 75 to 90 percent of the total waste stream (Kunzler and Roe 1995). In 1999, United States residents, businesses, and institutions generated more than 230 million tons of municipal solid waste; of this, food waste accounted for some 10.9%, a total of approximately 25 million tons (EPA 2002). Consumers pay for these losses, directly, through higher prices, or indirectly, through taxes and trash collection fees (Mundy 2002).

In developing countries, food waste is generated from spoiled or discarded food that occurs primarily from poor storage and preservation techniques. The loss from restaurants and supermarkets isn't as great as it is in the U.S. because these institutions aren't as common. Overall, developing countries produce three times less solid waste than industrialized countries (Table 1), most of which (more than 40%) is vegetable and putresible material (Cointreau-Levine 1994). Despite significantly less solid waste generation, developing countries struggle to dispose of waste safely and through diverse methods.

Table 4-1. Waste generation rates in metric tons per capita per year (Cointreau-Levine 1994).

Country Financial Status	Low-income	Middle-income	Industrialized
Solid Waste Generation	0.2	0.3	0.6

Poor collection and disposal practices are common in developing countries, often servicing only 50 to 70 percent of urban residents (Cointreau-Levine 1994, Rushbrook and Pugh 1999). Open dumps are common, allowing free access to waste pickers, pest animals (especially flies, and occasionally—something I know from personal experience—larger critters like crocodiles), and they often produce unpleasant and hazardous smoke from slow-burning fires (SKAT 2002). Obviously, chemical and biological contaminants in these wastes can affect human and environmental health, quality of life, and working activities if they are not safely disposed and contained.

If environmentally safe disposal were required in developing countries, the most cost-effective technique for most would be a sanitary landfill. Unfortunately, costs and a lack of suitable infrastructure prevent the creation of these landfills in most developing countries. Compost is a technically viable alternative because the content of vegetable and putrescible material is high in developing countries' waste streams (Cointreau-Levine 1994). However, the market is typically too poor: most farmers exist at subsistence levels and cannot afford to cover the cost of composting and transporting of compost products (Cointreau-Levine

1994). Specialized markets exist for compost (i.e., pottery, soil, horticultural farms, and intensive vegetable crop farms), but the total demand is usually too small to be economically viable.

In the U.S., solid waste is disposed of in sanitary landfills. These landfills are designed and operated with engineering techniques that minimize the pollution of air, water, and soil, and other risks to humans and animals. Incineration, composting, recycling, and resource recovery are also common waste management practices in the U.S, but are considerably less common in comparison to landfills. This variety of alternative disposal techniques is available in the U.S. because more money is available at both the state and federal level to subsidize these programs, as well as through individuals who are willing to pay for better services. Aesthetic considerations are also taken into account in waste disposal, but they tend to be political issues and not technical ones (SKAT 2002)—a typical distinction in the developed world, where larger amounts of money provide waste institutions the ability to “focus on the finer things.”

In 1998, only 0.6 million tons of food waste was recovered (including paper for composting) from the 22.1 million tons generated (EPA 2000). This is a meager 2.6 percent of the total food waste generated (Table 2), while other recoverable resource such as paper, glass, and nonferrous metals recovered 41.6, 25.5, and 67.4 percent, respectively, of their generation totals (EPA 2000). There is a lot of room

for improvement in recovering food waste from municipal solid waste.

Data regarding the food waste generation, recovery and disposal in developing countries is not available, primarily due to the fact that these countries struggle to dispose of disease-causing waste, and food waste recovery (or monitoring, for that matter) is not a priority.

In low-income developing countries, recyclable materials comprise about 15 percent of the solid waste stream. As an economy improves, residents are likely to consume more packaged goods and generate more waste. In middle-income developing countries, recyclable materials comprise about 30 percent of the solid waste stream. In industrialized countries, recyclables comprise about 60 percent of the waste stream (Cointreau-Levine 1994). Paradoxically, the more industrialized the country, the more recyclable materials figure into the creation of products, regardless of whether or not the materials are actually recycled.

Table 4-2. U.S. food waste generated, recovered, discarded in the municipal waste stream, 1960 to 1998 (EPA Data Tables 1999).

Date	1960	1970	1980	1990	1995	1996	1998
Food Waste Generation							
Thousands of Tons Generated	12,200	12,800	13,000	20,800	24,740	21,850	22,130
Percent of Total MSW Generation	13.8	10.6	8.6	10.1	10.3	10.4	10.0
Food Waste Recovery							
Thousands of Tons Recovered	Neg.*	Neg.	Neg.	Neg.	570	520	580
Percent of Total MSW Recovered	Neg.	Neg.	Neg.	Neg.	2.6	2.4	2.6
Food Waste Discarded after Recovery							
Thousands of Tons Discarded	12,200	12,800	13,000	20,800	21,170	21,330	21,550
Percent of Total MSW Discarded	14.8	11.3	9.5	12.1	13.5	14.0	13.6

\*Neg. = Negligible, less than 5,000 tons or 0.05 percent.

From 1997 to 1999, the per capita food consumption (kcal/capita/day) in developing countries<sup>1</sup> was 2681 and industrial countries reported 3380 (FAO 2002). Interestingly, a McDonald's meal contains half the calories (1,250) consumed daily for a person in a developing country and that is only one meal of the day for an American.

In developed nations, especially the United States, obesity has increased at an alarming rate. Obesity puts people at risk for health problems such as heart disease, cancer, and diabetes. The size,

<sup>1</sup> Including Sub-Saharan Africa, Idem (excluding Nigeria), Near East, North Africa, Latin America, Caribbean, South Asia, and East Asia.

frequency, and content of meals have changed over time, and the theme of obesity and consumption is echoed in hundreds of popular weight-loss books. For example, in the last fifty years, the growth of McDonald's French fries has nearly tripled in calories per serving (Table 4-3). Of course, the fries aren't the only part of lunch. The total meal: a Big Mac, medium fries, and a medium drink contain 1,250 calories; super-size the meal—a common theme in Texas—and the calories total 1,610 (Andersen 2003). A typical result of this lifestyle: one survey found 15 percent of American children between the ages of 6 and 19 were seriously overweight, nearly 9 million youths (CBS 2003). As a result of America's recognition of its obesity problem McDonald's is feeling the pressure to offer healthier choice and simplify its menu. To this end they are phasing out the Supersize fries and drinks.

Table 4-3. The growth of McDonald's French fries in the past fifty years (Andersen 2003).

Year	Serving Size	Description	Calories per Serving
1950s	Regular	Only one size	200
1970s	Large	"Regular" fries are now "Small"	320
1980s	Large	"Large" is now "Regular"	400
1990s	Super-size	New category added	540
2000s	Super-size	Old "Super-size" is now "Large"	610

Getty and Evers (2003) state that the changes in the U.S. per capita food consumption are a function of a wide variety of socio-economic factors, particularly diet and health concerns, relative prices,

real income, new products (particularly more convenient ones), an aging population, expanded advertising campaigns, smaller household, more two-earner households, more single-person households, and an increased proportion of ethnic minorities. This indicates that the problem is both very complex (given its wide number of potential influences) and quite simple (given the basic root of the problem) at the same time. Americans continue to eat away from home more often, reflecting the premium on convenience above nearly all else (Food and Agricultural Policy 2001).

In a recent CBSNEWS.com article, a U.N. agency stated that nearly one-third of all Europeans are obese due to fast-food consumption and sedentary lifestyles (CBS 2003). Once considered an American problem, obesity is becoming more prevalent in European countries. In Greece, officials say the problem is acute because people are turning away from the traditional Mediterranean diet and toward fast-food (CBS 2003), discarding both health and tradition. But, the U.S. still leads the world in weight problems with approximately 64 percent of Americans overweight and a third obese (CBS 2003).

The differences in waste management between the U.S. and developing countries boils down to quantity and money: the evolution of waste management has paralleled the increase in waste generation. The more waste you have, the more ways you look to deal with it, but the focal point is economic. Developing countries can't afford disposal at large scales, and often have to prioritize based upon health issues, if and when

possible; recycling is a distant idea when disease causing wastes are prevalent. In the U.S., health and sanitation issues were addressed a long time ago, so we can (and have) focused on other issues. In the U.S., the government subsidizes a great deal of waste management, and people have the “disposable” income to pay for disposal costs. Our lifestyles are oriented around convenience, and the primary problems and issues in waste management (along with any number of other social and environmental problems) can be traced directly to the consumption that is required to make food and life in general more convenient.

#### Education Curriculum

One of the greatest strategies of education is “to get them when they’re young.” There is more merit to this statement than simply indoctrinating the spongy mind of today’s youth. At a fundamental level children are wonderful creatures with the gifts of curiosity and wonder. They constantly ask questions and explore their world with all five senses. In many ways children are the first and greatest scientists—observing and experimenting. We tend to lose our sense of wonder and curiosity as we age and for this reason children are an excellent audience for introducing new ideas, like bioconversion. To this end I developed a curriculum entitled, *The Importance of Flies: My Garbage is Your Lunch*, for introducing bioconversion to a fifth grade class. While focusing on black soldier flies as food waste consumers, this curriculum also incorporates math skills and social issues of waste management.

## The Importance of Flies: My Garbage is Your Lunch

Lesson Summary: Students use the principle of trophic dynamics to explore the feeding habits of fly larvae.

General Goal: To have students understand how waste management affects the environment and that everything is a resource to some critter.

Duration: 1 week (Monday through Monday); First one and last day ~50 minute periods, intermediate days ~20 minute periods.

Learning Objectives: Upon completion of this lesson student will be able to:

- Describe the origins of food waste.
- Measure and describe food waste reduction and larvae weight gain.
- Explain the basic concept of trophic dynamics in terms of primary consumers and detritivores.
- Use the ideas from food waste reduction and trophic dynamics to predict the effects of larvae on food waste management.

Prerequisite Knowledge/Skills for Students:

- Familiarity with concepts of species, insects, feeding habits,
- Ability to use Mettler balance, calculator, forceps

- A basic understanding of using hypothesis for prediction.

Equipment:

- Apples (one per student)
- Mettler balances
- Weigh boats
- Forceps (one per student)
- Plastic cups (one per student)
- Paper towel (one per student)
- Rubber band (one per student)
- Calculator (one per student)
- Data sheet (one per student) (Table 4-4)

Instructional Strategy:

1. Provide each student with an apple. Collect weight of apple and record on datasheet. Have students eat apple.
2. Weigh core (left over apple) after eaten and record on datasheet.
3. Determine how much apple was eaten and how much waste remains and record on datasheet.
4. Add up apple waste for entire class and record on datasheet.
5. Discuss how waste is generated from the food we eat (e.g. inedible parts, spoilage, left-overs), and discuss how much apple waste is

generated by the school, city, and country and how is it managed/disposed.

6. Determine school, city, and country apple waste generation using average individual apple waste.

Sample calculation:

Average apple waste (g) x School population = School apple waste (g) per day

7. Provide each student with a plastic cup. Weigh plastic cup and record on datasheet.
8. Place apple core in plastic cup. Weight plastic cup again and record on datasheet.
9. Provide each student with 25 black soldier fly larvae.
10. Weigh 25 black soldier fly larvae and record on datasheet.
11. Place larvae in plastic cup with apple core and cover with paper towel and rubber band to keep larvae from escaping.
12. Monitor daily making observations about color, texture, size, shape, smell of apple waste and size, activity, color, and location of larvae. Discuss observations as a class.
13. After six days remove 25 larvae (or all those found) from the apple waste. Count the number of larvae found and record on datasheet. Weigh the larvae and record on datasheet.

14. Weigh the plastic cup with remaining apple waste and record on datasheet.

15. Determine apple waste reduction and larvae weight gain.

Sample calculations:

$$[\text{Initial plastic cup and apple waste (g)} - \text{Final plastic cup and apple waste (g)}] - \text{Plastic cup (g)} = \text{Apple waste reduction (g)}$$

$$\text{Final larvae weight (g)} - \text{Initial larvae weight (g)} = \text{Larvae weight gain (g)}$$

16. Determine average apple waste reduction.

17. Determine school, city, and country apple waste generation using average individual apple waste.

18. Discuss larvae feeding effects on apple waste reduction.

19. Discuss trophic dynamics using apple as primary producer and larvae as secondary consumer and detritivores.

20. Tie into the experiment how changes in temperature and moisture may affect larvae feeding habits and waste reduction (e.g. evaporation). You would expect that abiotic factors place a significant role in the feeding habits because the larvae (and all critters) have a range of tolerance for most abiotic factors. Additional experiments can be done under different conditions (e.g.

high temperature, low moisture) or with different food waste (e.g. banana peel).

21. Debrief by discussing the value of small-scale experiments and the differences between these and real life. Controlled experiments are often used in science because there isn't enough time or resources available to study the occurrence in nature.

Discussion questions:

- What are the differences and similarities between real life and controlled experiments?
- How can you change a controlled experiment to improve its representation of real life?
- What concepts are demonstrated in this controlled experiment?

22. Discuss the lessons of these activities (and trophic dynamics in general) as they could help in decisions to plan human activities (such as food waste disposal).



## Storytelling and Science

Many of the greatest stories, such as Homer's *Odyssey*, remain powerful across time and culture because they explore many of the basic facets of the human condition: efforts to try to transcend limitations, become gods, face desperate circumstances, answer important (or trivial) questions, failing while risking everything, love and war. Heroes (and anti-heroes) sometimes fail, and sometimes win, but the story is often focused on this struggle. Some of greatest stories touch us because, like our own lives, their heroes may toil through terrible situations to reach their goal, and then the story ends ambiguously (did Odysseus really win or lose?). This ambiguity focuses our thoughts into internal, sometimes lively or even heart-rending debates long after the book is put away.

But storytelling pervades all fields of knowledge, and should not be simply a subdivision of academic literature departments. The ultimate point, beyond any personal satisfaction, of *any* endeavor in the search for knowledge is to be able to explain what we find to others. This explanation is a form of storytelling. Scientific writing *is* storytelling, although its obsession with a presumed objectivity has led it away from trying to convey the breadth of the human experience toward merely reducing information to a set of related facts in which any possible relationship to subjectivity has been removed. The stories of science have constantly changed, well exemplified in the transitions of thought in physics from Copernicus to Newton to Einstein. The lesson provided by the history of

science is that objectivity and truth are not the same thing, though you would be hard pressed to get most technicians to agree with that—objectivity and truth, to many scientists, are two sides of the very same coin. The constant use of the passive voice in science writing aids this illusion, by removing nearly every possible mention of people (particularly the scientist; one should not remember they're human lest one therefore assume they have human failings, casting the whole enterprise in doubt!). Some scientists are also good storytellers, when they convey information by placing it in its true context, relating information to our lives and dreams. Storytelling isn't afraid of the messy world. John Steinbeck (1941) once commented that, "It has seemed sometimes that the little men in scientific work assumed the awe-fullness of a priesthood to hide their deficiencies, as the witchdoctor does with his stilts and high masks, as the priesthoods of all cults have, with secret or unfamiliar languages and symbols. It is usually found that only the little stuffy men object to what is called "popularization," by which they mean writing with a clarity understandable to one not familiar with the tricks and codes of the cult. We have not known a single great scientist who could not discourse freely and interestingly with a child."

Typically, science writing is only concerned with trying to convey information. A key distinction between storytelling and scientific writing is not only stylistic, but also a change in content through contextualization. Science writing often focuses on presenting the pertinent scientific

information first and proceeding from there. Unfortunately, the increasingly dominant method of information communication and storage—in culture at large, as well as science—are through sound bytes, video clips, databases, or factoids. Information is often characterized by a series of segmented ideas of content that are not necessarily related; by content primarily described with numbers, measurements, and quantities; by content that presents life as static; and by definitions that are presented isolated from their larger context (Strauss 1996).

The sharing of scientific information even calls for special presentation qualities, usually a monotone, monorhythmic voice to create the impression of seriousness that implies authority. This type of presentation helps influence people to believe that information is fact and therefore truth. Once you've got the facts, mystery and imagination are put on hold or are irrelevant; content given simply as information does not invite us to question or wonder (Strauss 1996). Furthermore, we are reminded constantly that beauty should not keep company with facts; facts are meant to be lifeless, serious, and followed (Strauss 1996). The coming of the information age means that people from all walks of life communicate without context and therefore without meaning. Science is no different; science writing and education is all too often an act of depositing information in a savings account (the audiences' brains) in hopes that one day the information will be withdrawn for use. This "banking" concept of education and learning (described by Friere 2003) is

very different from story telling. Merely explaining ecological or biological relationships as just a series of facts is to explain them away.

But while science should (and does) tell a story, it doesn't have to be dry, lifeless, or unrelated to the whole. Great scientists have always known that truth is an unending journey of discovery, that imagination is the mother of great discoveries, and that beauty is as much a part of science as it is of art (Strauss 1996). Even Leonardo Da Vinci wrote on biology in his spare time: in his notebooks from 1510, *Selections from the Notebooks of Leonardo Da Vinci*, he ponders fossil seashells and concludes that the Noachian flood could not have laid them down. His interest in the beauty of the seashells lead to questions about their origin and existence, setting him on the journey of inquiry and discovery.

Unlike science writing, which all too often only provides an explanation of the natural world (Drury 1998), storytelling also offers meaning and understanding. Explanation may be useful to win arguments and get papers published, but understanding provides context, the key that grounds us in the world. In most stories, the message or content speaks about the relationship, or lack of relationship, between an individual and aspects of the outer world. Storytelling also brings ideas and facts into a rich, value-laden world. In doing so, information is translated into images, pictures, and symbols, exciting our imagination and sense of wonder, something often lacking in typical scientific prose. However, it is more likely a listener will remember an image than anything

else. A good story shows what it wants to tell; natural facts are fantastic images, and images such as an apple or a maggot are already telling a meaningful story (Moore 1991; Strauss 1996). Taken together, this is life. Combining this approach with the facts and explanations of science can help convey an entire context more easily, and the interaction between the teller/lecturer and the audience/students can create help meaning in the present (Strauss 1996; Friere 2003).

With personal experiences, research and scientific observation of the world, we are constantly building a body of potential story material. Our skill as storytellers (lecturers!) is directly proportional to the degree of our attentiveness (Strauss 1996). This is important in developing motivation for a given activity such as studying bugs. If we pay attention our curiosity is often engaged. A motivation for anything is equally important for learning as is IQ, good schools or the best teachers.

The compartmentalization of information in science writing can be transformed usefully by weaving together beauty and fact into a verbal journey, which can engage a listener throughout, not just at the conclusion. The National Public Radio storyteller Garrison Keillor gives us the big point at the end, but we're not in a hurry to get there because we're enjoying the little points along the way. In this way, all of the content along the way is related to the outcome of the journey.

The cultures of scientists and historians is really one of inherited oral tradition, and remembering that can help us to relate facts that help

convey the passion we have for the world we work within, to build the facts that touch us most into experiences complete with senses, images, relationships and journeys—in short, to make stories. A good scientist can relate, with good scientific writing, their passionate pursuits of the mysteries of the world. Leopold, Muir, Carson, and Eiseley, were all good scientists and teachers of natural history, but were also great storytellers, and as such, made their mark well beyond their narrow scientific specializations. They are exemplars of the goal to bring science to the public in ways that aren't boring, obscure, and tedious. At the heart of brilliant science is a wonder for this awe-inspiring, heart-breaking, beautiful world in which we *live*.

Science remains powerful today because of its influence over the development of human (specifically western) civilization over the past 200 years. Strong science, that which effectively harnesses the powers of prediction, has led to healthier lives, greater wealth, and stronger technologies. However, the material benefits of science have overshadowed the explanatory powers and meaning of storytelling, marginalizing it to the fringes of scientific culture. Unfortunately, several misconceptions about the methods and results of science, such as objectivity, value-free science, and the search for Truth, have set science writing ahead, and have led to the assumed superiority of science writing over the story.

The goal of objectivity in science is to avoid human bias, but the common use of the term mistakenly assumes that we have simultaneously banished all value. The authority of objectivity in science is what has helped minimize the whimsical and capricious values of the story. While science may be rigorous and done in an objective manner, it is never value-free; the very structure of science, as well as its products, are always associated with values. The importance of values is often hidden or even actively refuted within the scientific community, usually for fear that people will distrust information soaked in values. However, good science cannot exist apart from the open awareness of the values and judgment upon which science rests.

With the understanding that science is necessarily value-laden comes the idea that good science is never the search for Truth (capital “T”), and one implicitly understands that the truth of a scientific result is conditional (thus, lowercase “t”). However, science and science writing today, whether in actual pronouncement or not, usually conveys to the public an authority on Truth and the search for Truth. These science stories are not good storytelling for the very reason that they implicitly establish a Truth. Likewise creationist stories are not good stories because they also explicitly imply a Truth to the story.

Storytelling, on the other hand, is considered an art for those who interact with children, weaving fictional tales solely for entertainment. Thus, there is no Truth in storytelling, especially when compared to

science writing. This may well be the case if your focus is on the content of a few stories such as Peter Pan or Cinderella. However, storytelling is more than a collection of fairytales. Great storytellers of nature include Barry Lopez, with his wolves and mysteries of the arctic, or Loren Eiseley's retelling of the origin of this planet and describing humans as descendents of slippery aquatic creatures forced to explore life on land. Both science writing and storytelling can tell the history of our planet and its origins; the difference is the way it relates to the reader/listener and the meaning, which is imparted. Like storytelling, science writing should be about the search for truth (little "t"), the description and exploration of experiences common to all people. A story relates common experiences and gives them meaning. Both science writing and story telling have facts, but it is how they use the facts that are important.

Laws, theories, hypotheses, and facts are important terms in science, but a hierarchical relationship does not necessarily exist among each of these terms. A theory in science writing is an explanation of a fact or facts that has relevant support, but it does not suggest proof nor is it as established as a law of nature. Several theories can explain a single fact. A fact, to use the phrase of Gould (1983), is a piece of information with which it would be perverse to disagree with (as a rational person). Facts are not truths, but they are established to an extent that no reasonable person would disagree, such as a ball will fall toward the ground when dropped from the roof. A theory is not less truthful or useful than a fact,

nor is a hypotheses a rung lower than a theory. They can be chronological at times, for example a series of hypothesis, once tested, may result in the development of a theory, and many tests of the theory over time can result in the statement of a law. Evolution, for example, fits this mold. Evolution is a fact—established to the point that it is perverse to disagree that it exists—as well as a theory, as a description of how this fact occurred (Gould 1983). Basically, the theory of evolution (or creationism for that matter) is a story, an explanation of the mechanism for the fact of evolution. We describe the world using facts, but we understand the world using theories, laws, or hypothesis. A good scientist should be skeptical of these theories, laws, and hypothesis if they suggest that they are Truth and the only means by which one can explain the facts observed.

The language of science is mathematics, considered by most the least arbitrary and universal language. Past mere observation, science relies on pieces of quantifiable information, which may be subjected to statistical analysis to determine a probability of a particular outcome. Science writing is generally never without tables and/or figures of the data and its results. The use of statistics, practically the single most used tool in modern science, further means that no ecologist or scientist can prove anything. In fact, proof is not the goal or function of science. Proof implies being 100% certain, and statistics tells us that in science nothing is 100%, everything is a probability. However, because most people do not have the background of statistical analysis—or even an elementary

understanding of it—the presence of datasets and probabilities carries a truth and authority that can be quite undeserved. As such, science writing appeals to a small number of people, generally other scientists. Because it is difficult to decipher the obscure datasets, probabilities, and technical methods, and because scientists typically do a poor job communicating, the general public does not read their articles, but assume that they are its superiority—at least until another study speaks to the contrary.

In this sense, relying on others (i.e., the scientific community) to solve problems and spur progress is not so different than the food waste management crisis discussed early. Both are a tragedy of the commons, in which no individual takes responsibility for the cultivation of waste disposal or scientific integrity. Again, the disposable attitude toward information is common. The public is often searching for the headlines or sound bites that can help dictate the course of one's behavior: 'Scientists believe two glasses of wine a day reduces the risk of cancer,' 'Environmental scientists claim recycling solves waste problems,' 'Dentists prove new gum to whiten teeth better,' 'Lack of ecofeminism course causes ecosystem crash at the Denton Landfill.' Attempting to gain an explanation or better meaning association with these factual conclusions requires time, thought, and dedication.

Despite the knee-jerk reaction of much of the public to appeal to science, some faith has been lost recently in certain segments of science with the increase of environmental and social problems. These problems

have arisen as a result of incomplete science, previously unsubstantiated faith in science, and lack of meaning in science. This loss of faith has hindered sciences that are not primarily linear and technology based (such as ecology), which has precluded significant progress in addressing the problems of social uses/abuses of science and technology.

Although storytelling is less common in science than it has been since the advent of ecology, its power is still evident. For example, during a hearing on whether the a portion of land should be annexed to the Grand Canyon and protected a scientist's testimony included the story of tracking a mountain lion across the landscape. The beauty and connectedness of this person to the land and the animal was a stark contrast to the use of datasets to summarize the demise of the mountain lion. The power of the story convinced a key Senator to vote for protecting the land, because what was originally "some land out west" and "some mountain lion" became a specific mountain lion with a name for its home and a life story experienced by a human and shared by others.

#### Children's Book

To introduce maggots to children I wrote a children's book that chronicles the life cycle of the black soldier fly. This book targets children six months to three years old. The format is modified into stanzas for the purposes of this dissertation. When completed the book will include illustrations and a stanza on each page. In addition to this children's book I would like to use the ideas under the "Benefits of Bugs" section as the

seeds for another book for older children. Instead of a fictional this book  
discuss the beauty of insects and their importance to humans.

### Maggie the Maggot

A brand new egg  
Hooray Hooray  
A whole new bug  
Starts today

On the very first second  
Of the very first day  
Happy Birthday Bug  
Is what we say

A few days pass  
While she warms in the sun  
Then pushing and pulling  
From the egg she comes

With no arms or legs  
Traveling looks grim  
But hunger forces her  
to try again

Feeling around  
with her clear little skin  
Stuck in the goo  
Her mother laid her in

But through her black eye spot  
She sees it's not far to move  
Cause the stuff all around  
Is yummy food

While beginning to eat  
She looks up  
Now and again  
For her brother to meet

Bigger she grows  
with her skin getting tight  
It cracks and loosens and

Out she comes with a fight

Soft and shiny  
Her new body shows  
But hungry for more  
Back to chewing she goes

She eats and she eats  
Shedding skin and growing fat  
Until one day she looks down  
And she's black as a cat

Not hungry for more  
She crawls all around  
Looking for a sleeping spot  
Hidden on the ground

Days pass  
with bug fast asleep  
Needing to stretch she wakes  
And out of her skin she peeks

Looking different now  
She has legs six to be exact  
Three body sections  
And two wings resting on her back

Take off was wobbly  
But once in flight  
She soars all day  
And into the night

When morning comes  
Her little green leaf  
Is covered with friends  
Including one named Pete

Sharing the skies  
And laughing with glee  
They fall in love  
And a Mom and Dad they'll soon be

Soon little bug  
Was looking around  
At soft and warm spot  
For her eggs to settle down

In the quiet of night  
She hovers above  
The tiny new home  
For her children to love

By morning she's done  
And not one did she miss  
But before she's gone  
Each egg gets a kiss

Now it's goodbye bug  
A whole life ends  
But tomorrow we'll start  
a new cycle of friends

A brand new egg  
Hooray Hooray  
A whole new bug  
Starts today

## Conclusions

The specific research objectives for the social aspect of this project are:

- Investigate factors determining the acceptance of insects
- Research directions for community outreach by creating educational material including a children's book and 5<sup>th</sup> grade curriculum.
- Develop a set of guidelines and criteria important in designing and managing bioconversion system for cafeteria-size utilization potential

The social obstacles facing bioconversion can be overcome by implementing a variety of education tools, thus making it feasible. The background research for the public's dislike of insects, including flies and maggots, identified two key factors: insects as vectors for disease and insects as agriculture rivals. Black soldier flies are not known to carry any diseases nor attack agriculture crops. However, the public does view flies and maggots in particular as disgusting. This stigma is only overcome with repeated exposure and is most successful when introduced at a young age. To this end the 5<sup>th</sup> grade curriculum and the children's book were developed for implementation in elementary schools.

Guidelines for introducing bioconversion to the public should focus on education and should begin at the elementary school level, using the 5<sup>th</sup> grade curriculum. The children's book should be provided to all elementary schools and city libraries. In addition to the curriculum and book, a hands-on project for selected classrooms using larvae to bioconvert lunchroom waste is desirable. This should be not difficult because many schools participate in worm composting, which is not much different than larval bioconversion.

## CHAPTER 5

### BIOLOGICAL CONSIDERATIONS

#### Introduction

Currently, it is uncertain that *Hermetia illucens* will regularly consume all food waste diets. Previous studies indicate that this species will feed on poultry and cattle manure (Booram et al. n.d.; Sheppard 1983; Sheppard et al. 1995; Tingle et al. 1975), and while the species has been found in a variety of organic wastes, no studies were found comparing bioconversion results based on artificial food diets with varying protein, fat, and fiber content. For this study, five experiments were conducted: two experiments testing dog food artificial diets, one experiment with food waste loading, and two experiments with grease enhanced artificial diets.

The majority of experiments were conducted with a dog food diet because fiber, fat, and protein content was known and consistent. Although food waste was available and used in one experiment, the content (fat, protein, fiber) is highly variable as the cafeteria menu regularly changes. Experiments conducted with food waste require regular content analysis to allow for comparisons among diets, and this was both cost and time prohibitive. The dog food diets provide comparisons between artificial diets with higher or lower fat and protein contents, from which results may be extrapolated to suggest preferred food waste content for maximum efficiency of bioconversion. The three grease experiments used dog food as a bulking agent and vegetable frying oil

collected from grease traps in West Hall cafeteria. These experiments were necessary to determine if larvae would consume grease, and more specifically, what grease or fat content in a diet could the black soldier fly larvae successfully process. Results are useful, particularly to the City of Denton's Wastewater Division, because grease buildup in sewers is a common and expensive problem.

### Materials and Methods

The University of Georgia at Tifton's Coastal Plain Experiment Station provided the larvae in these experiments. Eggs collected in "egg traps," made of three layers of double-faced corrugated cardboard (Booth and Sheppard 1984) glued together and cut into 2.5 by 5cm blocks, were placed in two 414ml plastic cups with lids (Gladware®, Oakland, CA) (when received from the University of Georgia at Tifton) in a 30°C, 12L:12D photoperiod incubator. Newly hatched neonates were reared on Gainesville House Fly Diet consisting of 50% wheat bran, 30% alfalfa meal, and 20% corn meal (Hogsette 1992) mixed with water (50-70% moisture) in each 414ml cup. A paper towel held tightly over the cup with a rubber band contained roving larvae. After approximately six to thirteen days, larvae were transferred to a 709ml plastic container (Gladware®, Oakland, CA) and placed on the artificial diet. Incubator conditions including temperature (°C), relative humidity (%), and light intensity (lumens) were monitored at 60-minute intervals using a HOBO® H8 Logger (Onset Computer Corporation, Bourne, MA). Experimental diets

were applied regularly and diet application ceased when twenty prepupae were present in at least one replication; prepupae were removed from the diet residue with forceps. Individual wet weights of these twenty prepupae were recorded to determine variability in growth. Percent dry matter of prepupae was determined by weighing the prepupae, drying in an oven at 60°C until a constant weight was reached, and reweighing. Percent dry matter was calculated by dividing the residual weight by the initial weight and multiplying by one hundred. Remaining larvae and prepupae were removed from the diet residue and placed in the greenhouse.

The focus of bioconversion is not solely rearing *H. illucens*, but rearing them to efficiently consume food wastes. To evaluate diet consumption, two variable were considered: dry matter extraction, and conversion rate.

Dry matter extraction is the percent of diet consumed on a dry matter basis. This provides a variable, which may be compared with diets of differing moisture contents. It also is a more accurate description of larval consumption because it is not subject to moisture evaporation.

Dry matter extraction was calculated using the following formula:

Dry matter extraction % =  $[1 - (\text{dry matter residue} / \text{dry matter diet})] \times 100$ .

Conversion rate is the amount of dry matter diet converted to dry matter prepupae expressed as a percentage. The greater the conversion rate the more efficient the diet is at turning out prepupae.

Conversion rate was calculated using the following formula:

Conversion rate % = [dry matter prepupae / dry matter diet].

Variables were evaluated using a one-way ANOVA or Kruskal-Wallis statistical analysis, and Independent t-test or Mann Whitney U test ( $\alpha = 0.05$ ).

#### Adult Colony

Initial eggs were provided in May 2001 by the University of Georgia at Tifton's Coastal Plain Experiment Station in order to start a colony at the University of North Texas. Larval rearing and adult emergence in controlled incubators was successful, but adult mating and ovipositing were plagued with problems. First attempts at an adult colony were made in a 2 by 2 by 2m, 7.1 by 5.5 mesh per centimeter Lumite® screen cage (BioQuip®, Gardena, CA) located in the University of North Texas Biology Department's greenhouse. Prepupae were transferred from the incubator to a open-topped plastic bucket in the cage to allow for emergence. Environmental conditions and associated adult emergence and oviposition with the cage were monitored. A portion of adults did emerge and observations indicate greatest emergence occurred at higher

temperatures. Mating was observed rarely and only in June, July, and August of 2001 when temperatures in the greenhouse were the highest, averaging 30°C , 60 to 90% relative humidity, and full exposure to natural sunlight. These observations are consistent with the literature. Very few egg masses were collected, but those that were hatched in the incubator.

With little success getting eggs in the greenhouse, secondary attempts at establishing an adult colony were made in the Bioconversion Laboratory, a 6 by 7 by 2m insulated metal building (Lonestar Carports, Fort Worth, TX). Heating and cooling were provided by an electrical heat pump. With no access to direct sunlight, artificial lights (Reptile Light/H00) were used to simulate natural exposure. Adults were not observed mating and no egg masses were laid under artificial light conditions, despite optimal temperatures and humidities.

In order to maintain an adult colony providing a continuous supply of eggs, a greenhouse is necessary which is large enough to contain a 2 by 2 by 2m Lumite® screened cage. The greenhouse must have temperature control and maintain a 30°C and 60 to 90% relative humidity environment with exposure to full sunlight. Egg traps need to be monitored, collected, and replaced on a regular basis. Alternatively, should an open system be desired, in which adults mate and lay egg masses directly on or above food waste held in tables, a cage and egg traps are not necessary. However, the open system should be housed in a

greenhouse able to provide full exposure to sunlight and high temperatures.

#### Artificial Diet Experiment 1

On August 31, 2002 eggs were collected from the University of North Texas greenhouse and placed in two 414ml plastic cups with lids (Gladware®®, Oakland, CA) in a 30°C, 12L:12D photoperiod incubator. Eggs in container A hatched on September 5 and eggs in container B hatched on September 6, 2002. Newly hatched neonates were reared on Gainesville House Fly Diet. On September 12 approximately 540 larvae (270 six day-old and 270 seven day-old larvae) were transferred to a 709ml plastic container. The number of neonates was determined by weighing an individual larvae and recording the wet weight. This was repeated with 10 individual larvae from each container (Table 5-1). Separate mean wet weights were calculated for the six-day old larvae and the seven-day old larvae (Table 5-1). The mean wet weights of the six and seven-day old larvae were used to determine the approximate number of larvae in the replicates (Table 5-2). The Low Fat/Protein treatments and replicate 1 of the High Fat/Protein used 7 day-old larvae while the remaining replicates used 6 day-old larvae (Table 5-2).

Table 5-1. Wet weight (g) of 6 and 7 day-old black soldier fly larvae in Artificial Diet Experiment 1.

Individuals	Container A: wet weight (g) 7day-old larvae	Container B: wet weight (g) 6 day-old larvae
1	0.019	0.002
2	0.015	0.002
3	0.011	0.002
4	0.004	0.002
5	0.002	0.002
6	0.010	0.001
7	0.010	0.001
8	0.003	0.005
9	0.018	0.002
10	0.008	0.001
Average	0.010	0.002

Table 5-2. Wet weights (g) of 540 6\* and 7 day-old black soldier fly larvae in Artificial Diet Experiment 1.

Treatment	Replicate 1	Replicate 2	Replicate 3
Low Fat/Protein	5.56	5.54	5.63
High Fat/Protein	5.64	1.1*	1.10*
Mix	1.07*	1.09*	1.09*

Table 5-3. Mean larval number and wet weights, diet applied, and grams of diet per larvae in Artificial Diet Experiment 1.

Treatment	Larvae	Larvae wet weight (g)	Diet applied (g)	Diet (g)/larvae
Low Fat/Protein	542	5.58	633.54	1.17
High Fat/Protein	542	2.61	633.85	1.17
Mix	534	1.08	633.74	1.19

Three artificial diet treatments were employed, each one with three replications. The treatments were: (1) Nutro's Nature Choice Lite dog food; (2) Nutro's Nature Choice High Energy dog food; (3) Equal mixture

of Nutro's Nature Choice Lite and High Energy dog food. Each treatment had approximately 72% moisture maintained by the addition of deionized water. In each replication, approximately 540 six or seven day-old larvae were transferred to a 709ml plastic container (Gladware®, Oakland, CA). Approximately 72% moisture content diet was added five days a week over 13 days on an incremental schedule because larger larvae consume more than neonates. The dry matter of the diet was determined by calculating the gram weight of dog food and gram weight of water applied. Larvae in each replication were fed approximately 633g of diet over 13 days (Table 5-4). Temperatures ranged between 27.91 and 29.10°C in the incubator. Relative humidity experienced larger swings during this period from 50 to 75%. Light intensity maintained a 12 hour light to 12 hour darkness periodicity with extremes ranging from 0 to 135 lumens.

Table 5-4. Diet applied (g) to three diets in Artificial Diet Experiment 1.

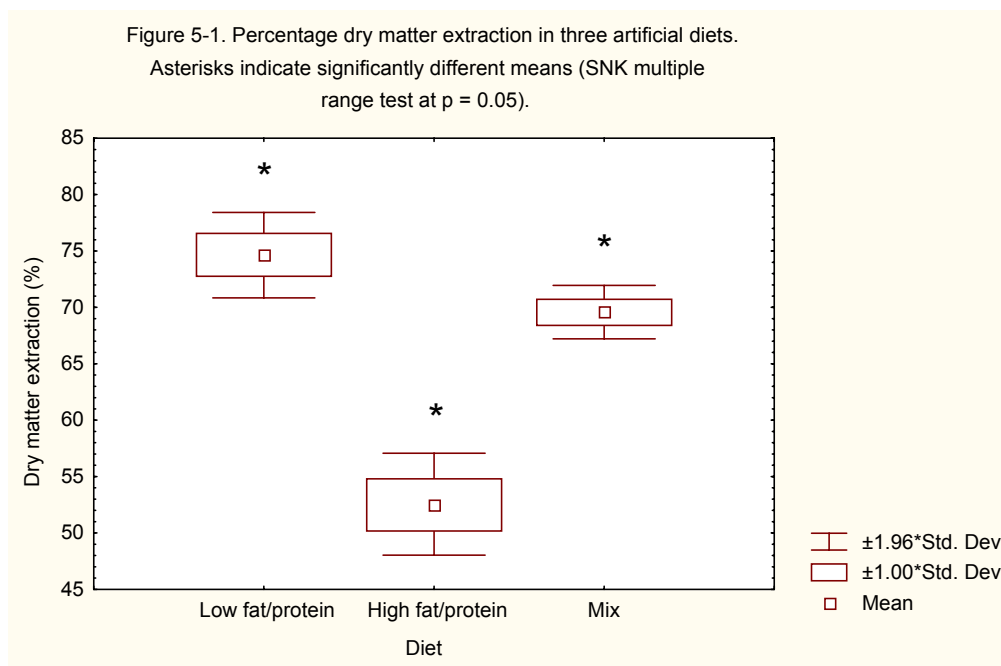
Date	Low Fat/Protein Diet (g)			High Fat/Protein Diet (g)			Mix Diet (g)		
	Replicate			Replicate			Replicate		
	1	2	3	1	2	3	1	2	3
9/12/02	50.25	50.32	50.31	50.05	50.47	50.51	50.02	50.11	50.54
9/14/02	50.19	50.39	50.39	50.40	50.53	50.08	50.29	50.53	50.43
9/16/02	50.09	50.24	50.12	50.49	50.91	50.81	50.26	50.15	50.07
9/17/02	70.18	70.30	70.90	70.15	70.37	70.80	70.24	70.39	70.19
9/18/02	70.62	70.14	70.19	70.94	70.07	70.34	70.92	70.16	70.88
9/19/02	70.30	70.40	70.59	70.16	70.16	70.59	70.68	70.26	70.91
9/20/02	70.61	70.84	70.06	70.36	70.07	70.35	70.20	70.19	70.59
9/23/02	100.41	100.60	100.00	100.46	100.06	100.61	100.61	100.55	100.80
9/24/02	100.66	100.11	100.84	100.99	100.02	100.80	100.32	100.37	100.55
Total	633.31	633.34	633.97	633.99	632.66	634.89	633.54	632.71	634.96

## Results: Artificial Diet Experiment 1

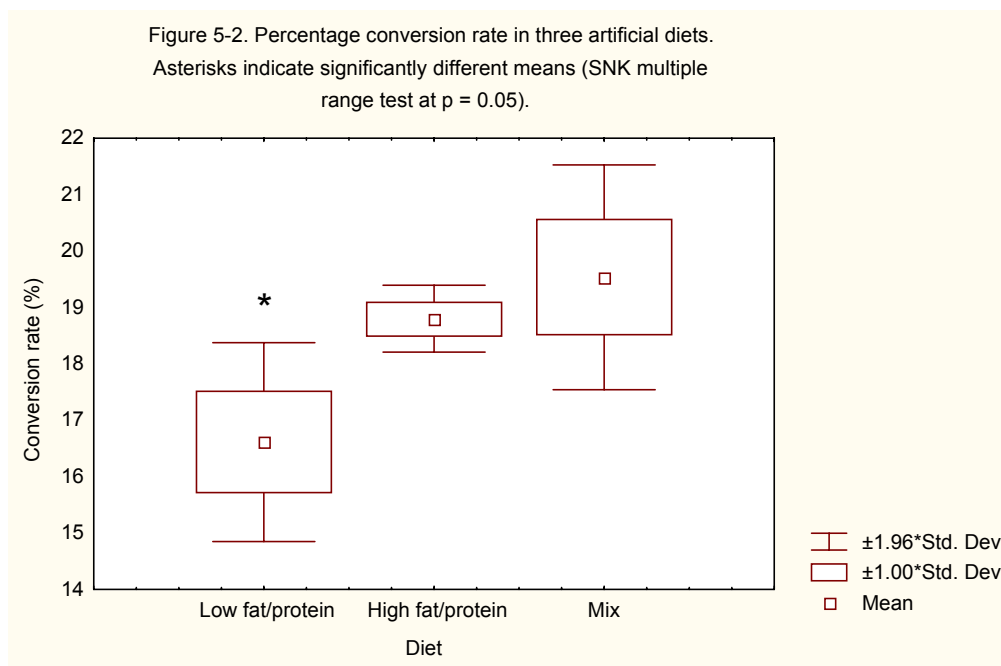
Of the three diets, dry matter extraction (%) was greatest in the Low Fat/Protein Diet. Mean dry matter extraction of the three artificial diets ranged from 52.56 to 74.63, and were highly significantly different (one-way ANOVA,  $F = 114.53$ ,  $p < 0.0001$ ). A SNK multiple range test ( $\alpha = 0.05$ ) separated the means into three statistically distinct groups: High Fat/Protein  $52.55 < \text{Mix } 69.58 < \text{Low Fat/Protein } 74.63$  (Table 5-5). Variability was greatest in the High Fat/Protein diet and possibly a result of different wet weights of the initial larvae used among the replicates (Figure 5-1). Replicates 2 and 3 of the High Fat/Protein diet had six day-old larvae that were almost five times smaller than the seven day larvae used in replicate 1.

Table 5-5. Dry matter extraction, conversion rate, days to prepupae, prepupae dry matter, and prepupae wet weight of three artificial diets in Artificial Diet Experiment 1. Mean and sample sizes are listed. Asterisks indicate groups with statistically different mean from SNK multiple range test ( $\alpha = 0.05$ ).

Treatment	Dry matter extraction (%)	Conversion rate (%)	Days to prepupae	Prepupae dry matter (%)	Prepupae Wet weight (g)
Low Fat/Protein	74.63* (3)	16.61* (3)	21* (3)	36.37 (3)	0.15
High Fat/Protein	52.55* (3)	18.8 (3)	19 (3)	39.58 (3)	0.16
Mix	69.58* (3)	19.53 (3)	19 (3)	35.61 (3)	0.19*

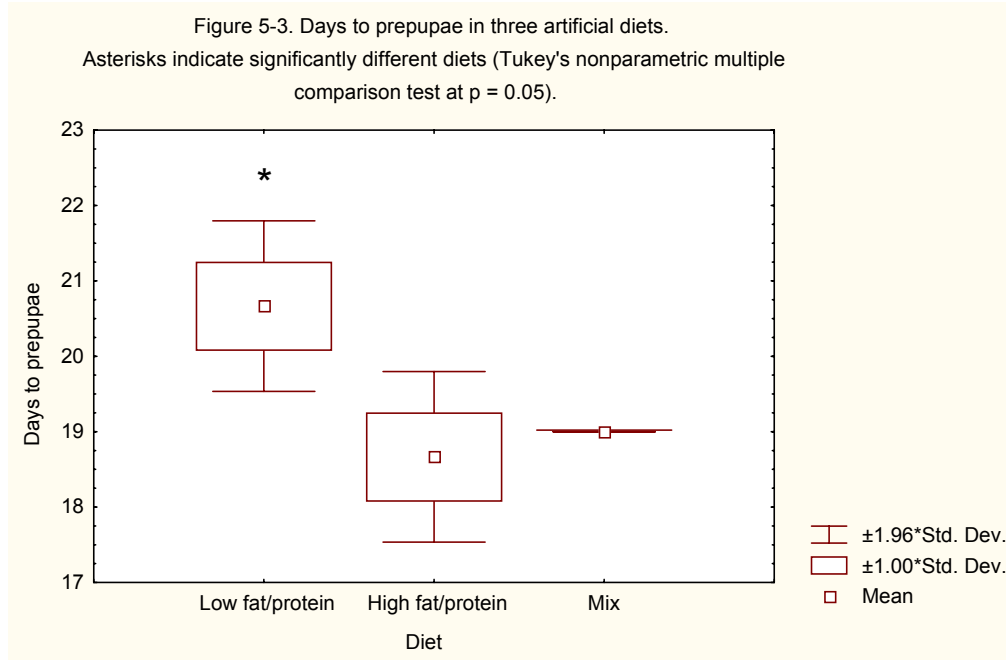


The conversion rate (%) was similar in the three diets, with means ranging from 16.61% (Low Fat/Protein), 18.8% (High Fat/Protein), and 19.53% (Mix) (Table 5-5). Mean conversion rate of the three artificial diets were highly significantly different (one-way ANOVA,  $F = 10.76$ ,  $p < 0.01$ ). A SNK multiple range test ( $\alpha = 0.05$ ) separated the means into two statistically distinct groups: Low Fat/Protein  $16.61 < \text{High Fat/Protein}$   $18.80 < \text{Mix}$  19.53 (Figure 5-2).



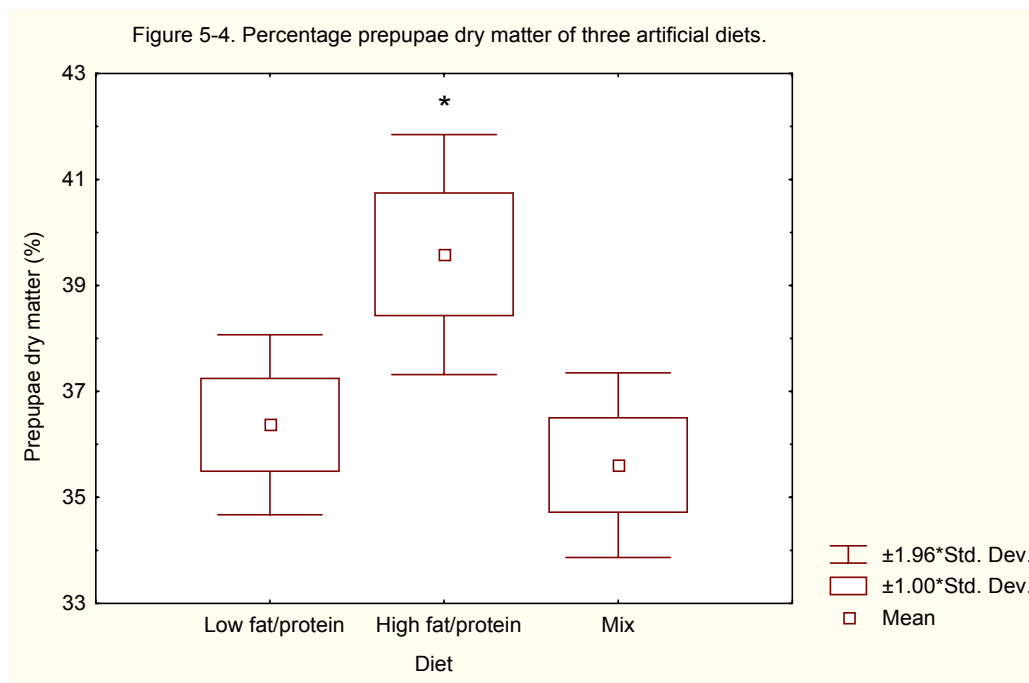
Prepupal development was faster in both the High Fat Protein and Mix Diets. Diet was applied over 13 days until the High Fat/Protein Diet replicate 2 developed 20 prepupae, after which diet application ceased for all replicates. Days to 20 prepupae was defined as the number of days since hatch, not inoculation in the artificial diet.

Days to twenty prepupae were significantly different among the three diets (Kruskal-Wallis one-way multisample test,  $p=0.034$ ). A SNK nonparametric multiple comparison test ( $\alpha = 0.05$ ) separated the rank sums of the three diets into two statistically different groups: High Fat/Protein = Mix < Low Fat/Protein (Table 5-5). The Mix Diet had no variability, with all replicates reaching twenty prepupae in 19 days, while the Low Fat/Protein and High Fat/Protein Diet replicates varied slightly (Figure 5-3).



Mean prepupae weight (g) of the three diets was significantly different (one-way ANOVA,  $F = 44.24$ ,  $p = 0.0001$ ) (Table 5-5). A SNK multiple range test ( $\alpha = 0.05$ ) separated the means into two statistically different groups: Low Fat/Protein  $0.15 =$  High Fat/Protein  $0.16 <$  Mix.

Mean twenty prepupae dry matter (%) of the three diets was significantly different (one-way ANOVA,  $F = 13.91$ ,  $p = 0.0056$ ) (Table 5-5). A SNK multiple range test ( $\alpha = 0.05$ ) separated the diets into two statistically distinct groups: Low Fat/Protein  $36.37 =$  Mix  $35.61 <$  High Fat/Protein  $39.58$  (Figure 5-5).



The Low Fat/Protein Diet had the highest dry matter extraction and days to prepupae and the lowest conversion rate, suggesting that the larvae had to work harder to meet their metabolic requirements and consumed more diet overall. Yet, the prepupae in this diet remained smaller than the High Fat/Protein and Mix Diets and took longer to reach prepupae, possibly because of a lack of sufficient nutrients. Adequate nutrients may account for the lowest dry matter extraction in the High Fat/Protein Diet requiring more consumption. The larvae benefited from the High Fat/Protein Diet by reaching prepupae more quickly, yet the efficiency of bioconversion is not favored because not as much diet is consumed and thus disposed. The optimal diet for bioconversion may be the Mix Diet because the larvae meet their nutritional needs while dry

matter extraction and conversion rates remain high. This diet also produced the largest prepupae, which are more profitable if sold as feedstuff.

#### Artificial Diet Experiment 2

In October, 2002 eggs were collected from the University of Georgia at Tifton Field Station and mailed to the University of North Texas where they were placed in 414ml plastic cups with lids (Gladware®, Oakland, CA) in a 30°C, 12L:12D photoperiod incubator. Eggs hatched on October 21, 2002. Newly hatched neonates were given Gainesville House Fly Diet. On October 28, 2002, approximately 100 seven day-old larvae were transferred to each 709ml plastic container. The number of neonates was determined by counting 100 individual larvae. Weights of the 100 larvae for each replicate are recorded in Table 5-6.

Table 5-6. Larval number and mean wet weights, diet applied, and grams of diet per larvae in Artificial Diet Experiment 2.

Treatment	Larvae	Larvae wet weight (g)	Diet applied (g)	Diet (g)/larvae
Low Fat/Protein	100	0.35	383.02	3.83
High Fat/Protein	100	0.38	382.13	3.82
Mix	100	0.37	382.10	3.82

Three artificial diet treatments were employed, each one with three replications. The treatments were: (1) Nutro's Nature Choice Lite dog food; (2) Nutro's Nature Choice High Energy dog food; (3) Equal mixture of Nutro's Nature Choice Lite and High Energy dog food. Approximately

68% moisture content diet experimentally determined (Table 5-7) was added five days a week over 11 days. Larvae in each replication were fed approximately 382g of diet over the 11 days (Table 5-8).

Temperatures ranged between 27.52 and 29.1°C in the incubator. Relative humidity experienced large swings during this experiment and ranged from 24.3 to 62.4%. Light intensity maintained a 12 hour light to 12 hour darkness periodicity with extremes ranging from 0 to 123 lumens.

Table 5-7. Experimental diet dry matter of Artificial Diet Experiment 2.

Diet	Replication	Mean dry weight (g)
Low Fat/Protein	1	32.91
Low Fat/Protein	2	32.49
Low Fat/Protein	3	32.80
High Fat/Protein	1	32.49
High Fat/Protein	2	32.01
High Fat/Protein	3	32.12
Mix	1	31.76
Mix	2	32.83
Mix	3	31.90

Table 5-8 Diet applied (g) to three diets in Artificial Diet Experiment 2.

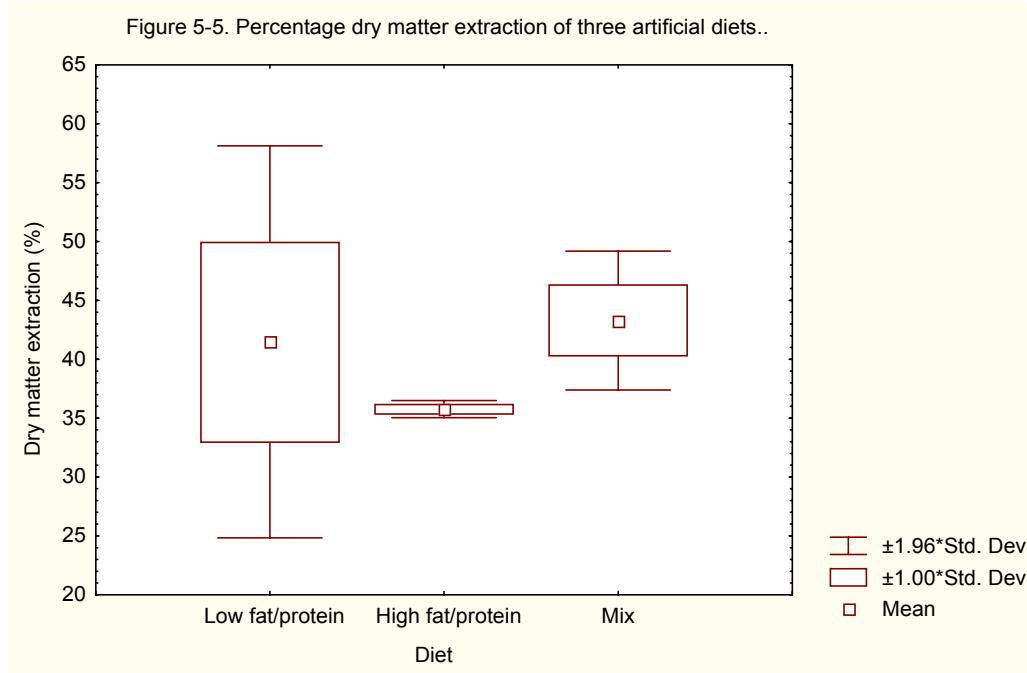
Date	Low Fat/Protein Diet (g)			High Fat/Protein Diet (g)			Mix Diet (g)		
	Replicate			Replicate			Replicate		
	1	2	3	1	2	3	1	2	3
10/28/02	30.20	30.06	30.53	30.46	30.26	30.21	30.32	30.77	30.80
10/29/02	50.65	50.78	50.29	50.28	50.49	50.39	50.05	50.38	50.14
10/31/02	50.91	50.54	50.29	50.13	50.96	50.59	50.39	50.14	50.65
11/3/02	50.81	50.23	50.64	50.27	50.51	50.30	50.05	50.32	50.89
11/4/02	100.71	100.35	100.70	100.31	100.07	100.42	100.49	100.01	100.33
11/7/02	100.33	100.40	100.66	100.09	100.23	100.42	100.01	100.29	100.25
Total	383.61	382.35	383.11	382.34	382.52	381.54	381.36	381.90	383.06

## Results: Artificial Diet Experiment 2

Of the three diets, dry matter extraction (%) was greatest in the Mix diet. Mean dry matter extraction of the three artificial diets ranged from 35.76% to 43.29%, and were not significantly different (Table 5-9). Despite little variability in the Low Fat/Protein and Mix Diets, high variability in the Low Fat/Protein Diet may have prevented separation of the means (Figure 5-6).

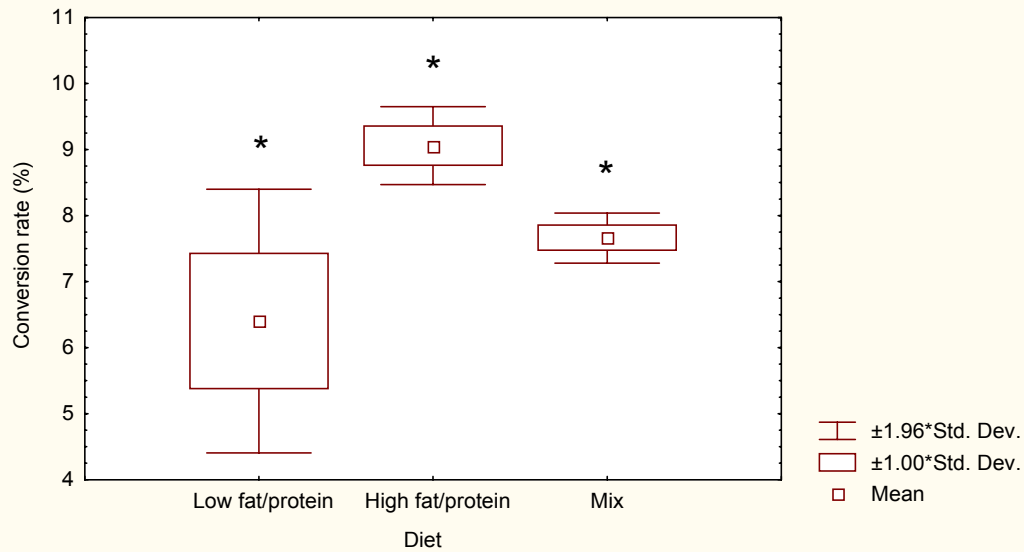
Table 5-9. Dry matter extraction, conversion rate, days to prepupae, prepupae dry matter, and prepupae wet weight of three artificial diets in Artificial Diet Experiment 2. Mean and sample sizes are listed. Asterisks indicate groups with statistically different mean from SNK multiple range test ( $\alpha = 0.05$ ).

Treatment	Dry matter extraction (%)	Conversion rate (%)	Days to prepupae	Prepupae dry matter (%)	Prepupae wet weight (g)
Low Fat/Protein	41.48 (3)	6.40* (3)	28* (3)	43.97* (3)	0.16* (3)
High Fat/Protein	35.76 (3)	9.06* (3)	22* (3)	40.38 (3)	0.24* (3)
Mix	43.29 (3)	7.66* (3)	23* (3)	40.17 (3)	0.20* (3)



Conversion rate (%) was significantly different among the three diets (one-way ANOVA,  $F = 13.64$ ,  $p = 0.006$ ). A SNK multiple range test ( $\alpha = 0.05$ ) separated the three diets into two statistically distinct groups: Low Fat/Protein  $6.4 < \text{Mix } 7.66 < \text{High Fat/Protein } 9.06$  (Table 5-9). As with dry matter extraction, the conversion rate of the Low Fat/Protein Diet had high variability (Figure 5-6).

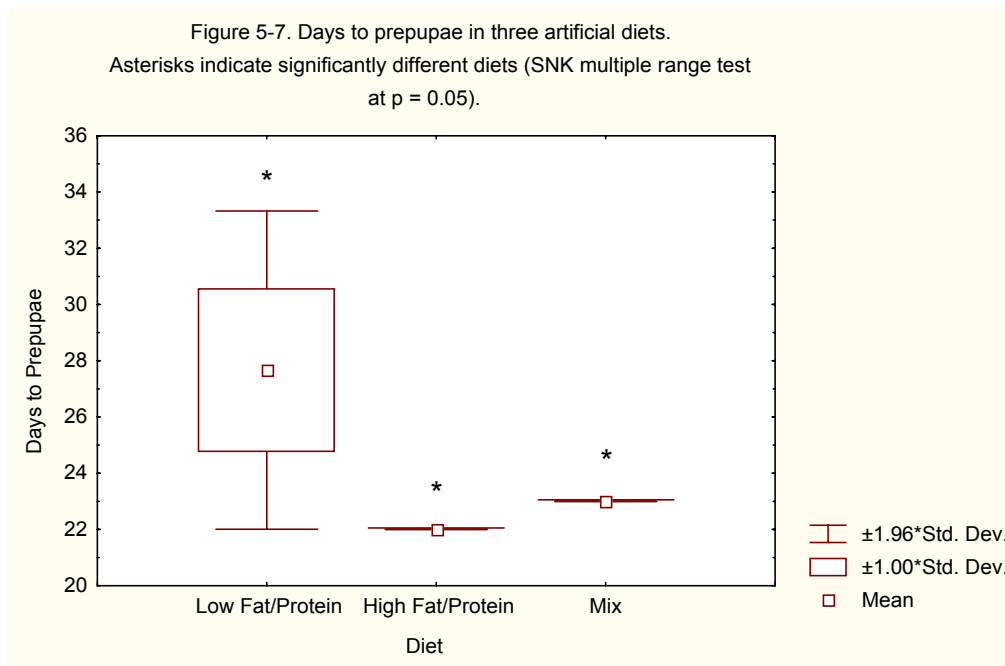
Figure 5-6. Percentage conversion rate of three artificial diets. Asterisks indicate significantly different means (SNK multiple range test  $p = 0.05$ ).



Prepupal development was faster in both the High Fat Protein and Mix diets. Diet was applied over 11 days until all the High Fat/Protein Diet replicates developed 20 prepupae, after which diet application ceased for all replicates. Days to 20 prepupae was defined as the number of days since hatch, not inoculation in artificial diet.

Days to twenty prepupae were significantly different among the three diets (Kruskall-Wallis one-way multisample test,  $p=0.0204$ ). A SNK nonparametric multiple comparison test ( $\alpha = 0.05$ ) separated the rank sums of the three diets into three statistically different groups: High Fat Protein < Mix < Low Fat Protein (Table 5-9). The High Fat/Protein and Mix Diets had no variability, with all replicates reaching twenty prepupae in 15 and 16 days, respectively. However, the Low Fat/Protein Diet replicates

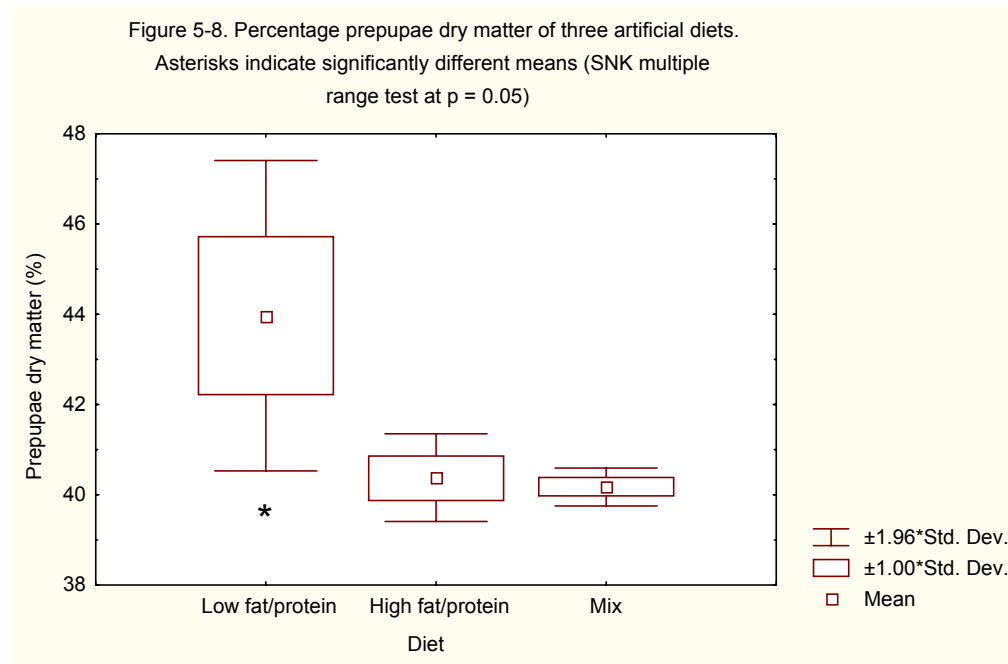
varied a great deal (Figure 5-7) with replicates reaching the 20 prepupae stage anywhere between 26 and 31 days.



Mean prepupae weight (g) of the three diets was significantly different (Kruskall-Wallis one-way multisample test,  $p < 0.0001$ ) (Table 5-5). A SNK nonparametric multiple comparison test ( $\alpha = 0.05$ ) separated the rank sums of the three diets into two statistically different groups: Low Fat/Protein 0.17 < Mix 0.21 < High Fat/Protein 0.24.

Mean twenty prepupae dry matter (%) of the three diets was significantly different (one-way ANOVA,  $F = 13.91$ ,  $p = 0.0056$ ). A SNK multiple range test ( $\alpha = 0.05$ ) separated the data into two statistically distinct groups: Mix 40.17 = High Fat/Protein 40.38 < Low Fat Protein

43.97 (Table 5-9). The Low Fat/Protein Diet experienced high variability, although it did not impact the separation of means (Figure 5-8).



The Low Fat/Protein Diet appears the least beneficial to the individual larvae because it produces smaller prepupae and takes longer to reach this stage. While this may not be an optimal diet for the larvae, it is unclear if a Low Fat/Protein Diet is more beneficial for bioconversion. With no significant difference among dry matter extraction (the best indicator of diet consumption), optimum diet content is uncertain in this experiment. The High Fat/Protein Diet produces the largest prepupae by weight and the most quickly suggesting they are receiving more adequate

nutrient to meet their metabolic and development needs compared to the Low Fat/Protein and Mix Diets.

#### Food Waste Loading Experiment

In early April, 2003, eggs were collected from the University of Georgia at Tifton Field Station and mailed to the University of North Texas where they were placed in 414ml plastic cups with lids (Gladware®, Oakland, CA) in a 30°C, 12L:12D photoperiod incubator. Eggs hatched on April, 19 2003. Newly hatched neonates were given Gainesville House Fly Diet in the 414ml cup. On April 25, 2003, 45 six-day old larvae were transferred to each 709ml plastic container. The number of neonates was determined by counting individual larvae. The weight of the larvae for each replicate was recorded in Table 5-10.

Table 5-10. Larval number and mean wet weights, diet applied, and grams of diet per larvae in Food Waste Loading Experiment.

Treatment	Larvae	Larvae wet weight (g)	Diet applied (g)	Diet (g)/larvae
Low Loading	45	4.79	450.00	10.00
High Loading	45	4.48	1050.00	23.33

Two loading rates were employed, each one with three replications. The treatments were: (1) High loading of ground food waste from West Hall Cafeteria, University of North Texas (2) Low loading of ground food waste from West Hall Cafeteria, University of North Texas. Approximately 54% moisture content diet, determined experimentally (Table 5-11), was added three days a week over thirteen days on an incremental schedule.

Larvae in the High Loading treatments were fed approximately 1050g and larvae in the Low Loading treatment were fed approximately 450g of diet over 13 days (Table 5-12).

Table 5-11. Dry weight (g) determination of ground food waste.

Treatment	Replication	Wet Weight (g) Date: 6/23	Dry Weight (g) Date: 7/2	Dry Matter (%)
High Loading	1	150.40	79.63	52.77
High Loading	2	149.56	81.24	54.07
High Loading	3	145.14	82.51	56.66
Low Loading	4	131.90	69.80	52.77
Low Loading	5	130.80	73.75	56.25
Low Loading	6	146.46	76.86	52.29
	Mean	142.38	77.30	54.14

Table 5-12 Diet applied (g) to two loading diets.

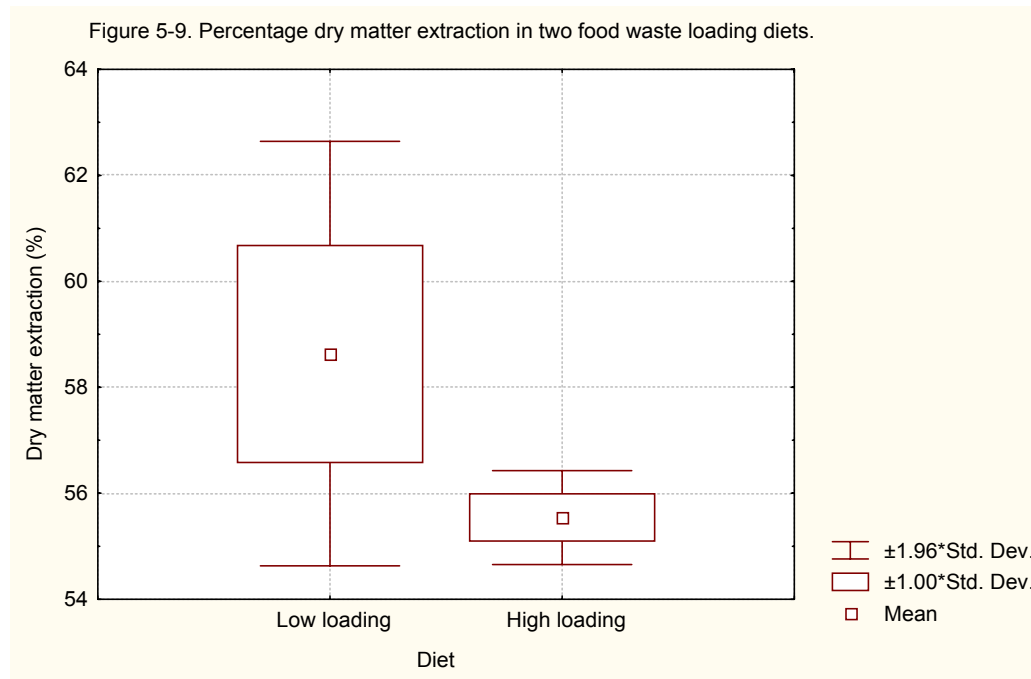
Date	Low Loading			High Loading		
	Replicate			Replicate		
	1	2	3	1	2	3
4/25/03	50	50	50	150	150	150
4/28/03	50	50	50	150	150	150
4/30/03	50	50	50	150	150	150
5/2/03	100	100	100	200	200	200
5/5/02	100	100	100	200	200	200
5/7/02	100	100	100	200	200	200
Total	450	450	450	1050	1050	1050

## Results: Food Waste Loading Experiment

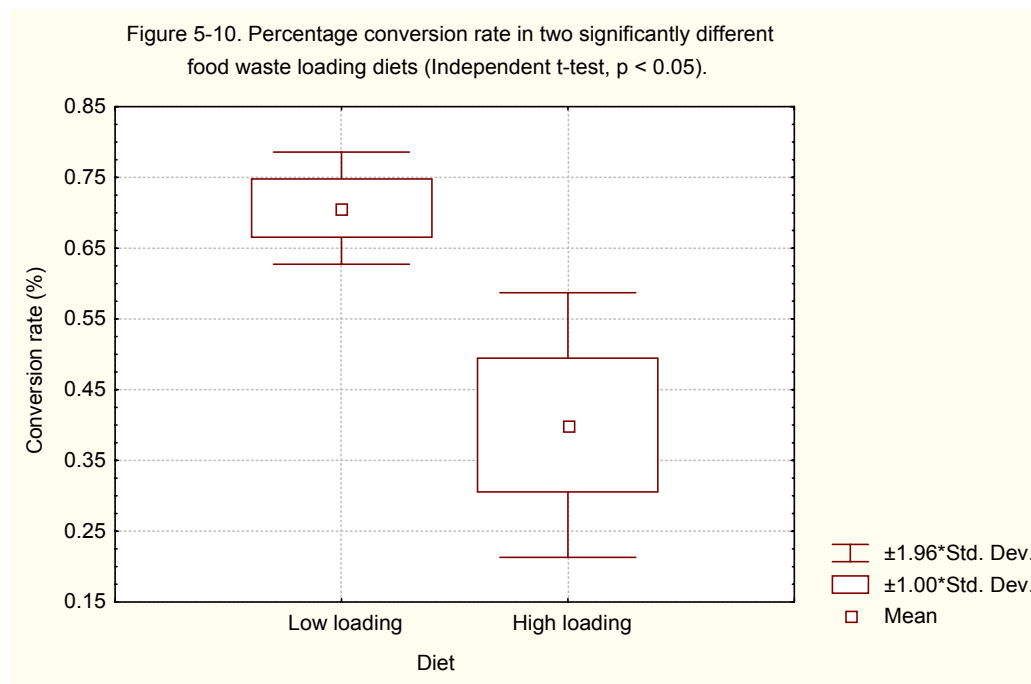
Of the two diets, dry matter extraction (%) was greatest in the Low loading diet, although not significantly different (Table 5-13). High variance in the Low Loading treatment may have contributed to the inability to separate the means (Figure 5-9).

Table 5-13. Dry matter extraction, conversion rate, days to prepupae, prepupae dry matter, and prepupae wet weight of two food waste loading treatments. Mean and sample sizes are listed. Asterisks indicate groups with statistically different mean from Independent t-test ( $\alpha < 0.05$ ).

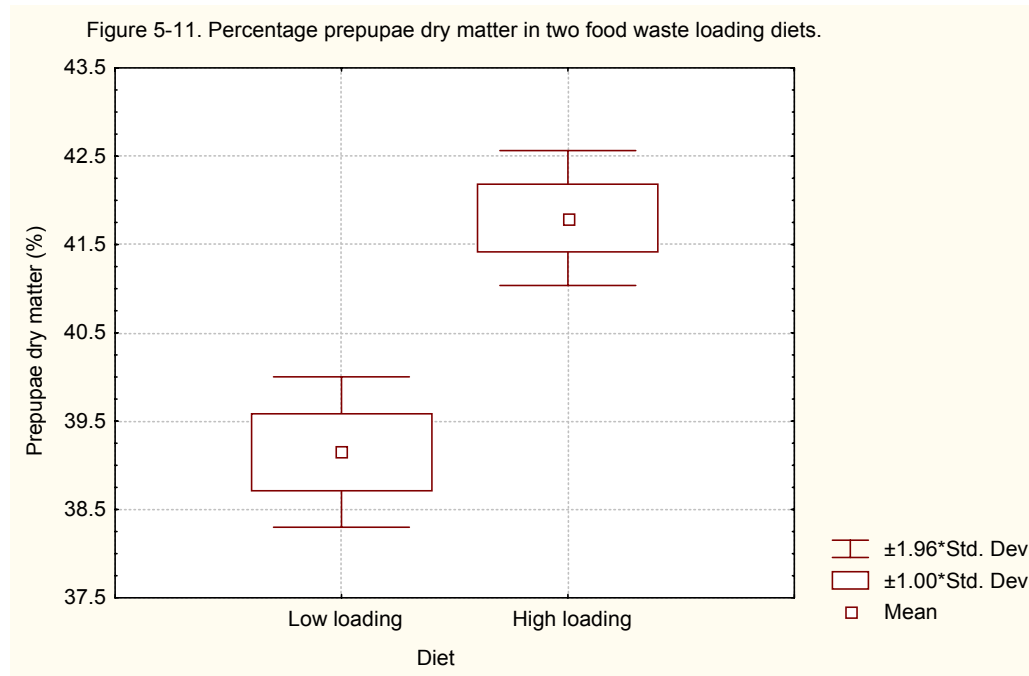
Treatment	Dry matter extraction (%)	Conversion rate (%)	Days to prepupae	Prepupae dry matter (%)	Prepupae wet weight (g)
High Loading	55.54 (3)	0.40* (3)	19 (3)	41.80 (3)	0.15 (20)
Low Loading	58.61 (3)	0.71* (3)	19 (3)	39.15 (3)	0.16 (20)



The conversion rate (%) was significantly different among the two food loading treatments (Independent T-test,  $p = 0.0069$ ), with means of High loading  $0.4 <$  Low loading  $0.71$  (Figure 5-10).



Prepupae were collected after thirteen days in both treatments, therefore no comparisons were made for the days to prepupae variable. The prepupae dry matter percent ranged from 39.15 (Low Loading) to 41.8 (High Loading) and were not significantly different ( $p=0.055$ ; Table 5-13, Figure 5-11).



This experiment failed to show differences in means among the variables, except conversion rate. Although the experiment sought to compare food waste loading and the grams of diet-to-larvae ratios differed among the treatments, both diets to larvae ratios may have been too large to show a difference among the treatments.

### Grease Enhanced Diet Experiment 1

In late April, 2003, eggs were collected from the University of Georgia at Tifton Field Station and mailed to the University of North Texas, where they were placed in a 414ml plastic cup with lid (Gladware®, Oakland, CA) in a 30°C, 12L:12D photoperiod incubator. Eggs hatched on May 1, 2003. Newly hatched neonates were given Gainesville House Fly Diet in the 414ml cup. On March 13, 2003, thirteen day-old larvae were transferred to nine 709ml plastic containers, with 123 larvae per container.

The number of neonates was determined by counting individual larvae.

Weights of the larvae in each replicate are recorded in Table 5-14.

Table 5-14. Larval number and mean wet weights, diet applied, and grams of diet per larvae in Grease Enhanced Diet Experiment 1.

Treatment	Larvae	Larvae wet weight (g)	Diet applied (g)	Diet (g)/larvae
Low Fat/Protein Diet (g)	123	8.62	401.23	3.26
Low Fat/Protein Diet with 17% grease (g)	123	8.64	481.18	3.91
Low Fat/Protein Diet with 33% grease (g)	123	8.52	552.12	4.49

Three artificial diet treatments were employed, each one with three replications. The treatments were: (1) Nutro's Nature Choice Lite dog food as the control; (2) Nutro's Nature Choice Lite dog food with 17% grease; (3) Nutro's Nature Choice Lite dog food with 33% grease. Each of the treatment's moisture content varied based on the amount of grease added. The Low Fat/Protein Diet was 70% moisture, Low Fat/Protein with 17% grease treatment was 58% moisture, and the Low Fat/Protein with 33% grease treatment was 47% moisture. Moisture content was determined by calculating the gram weight of dry dog food and grease together, and then dividing by the gram weight of water applied. Diet was added three days a week over ten days on an incremental schedule. Larvae in the Low Fat/Protein, Low Fat/Protein with 17% Grease, and Low Fat/Protein with 33% Grease were fed approximately 401g, 481g, and 552g of diet, respectively (Table 5-15).

The diet applied varied between the treatments because of the addition of grease. Each diet contained the same amount of Low Fat/Protein dog food with varying amounts of grease. This difference in diet application makes comparisons difficult, because the grams of diet per larvae are not consistent.

Temperatures ranged between 29.1 and 31.12°C in the incubator. Relative humidity experienced larger swings during this period and remained rather low, from 22.9 to 47.1%. Light intensity maintained a 12 hour light to 12 hour darkness periodicity with extremes ranging from 0 to 223 lumens.

Table 5-15 Diet applied (g) to three diets in Grease Enhanced Diet 1.

Date	Low Fat/Protein Diet (g)			Low Fat/Protein with 17% Grease Diet (g)			Low Fat/Protein with 33% Grease Diet (g)		
	Replicate			Replicate			Replicate		
	1	2	3	1	2	3	1	2	3
5/14/03	50.78	50.05	50.20	58.40	59.79	59.48	74.98	74.83	74.96
5/16/03	50.03	50.33	50.39	60.26	60.33	60.59	75.58	75.80	75.47
5/19/03	100.32	100.26	100.39	120.43	120.55	120.28	150.50	151.05	150.37
5/21/03	100.04	100.35	100.21	120.18	120.61	120.59	150.16	150.71	105.67
5/23/03	100.23	100.04	100.07	120.53	121.17	120.37	100.33	100.49	100.53
Total	401.40	401.02	401.26	479.80	482.45	481.30	551.46	552.88	552.01

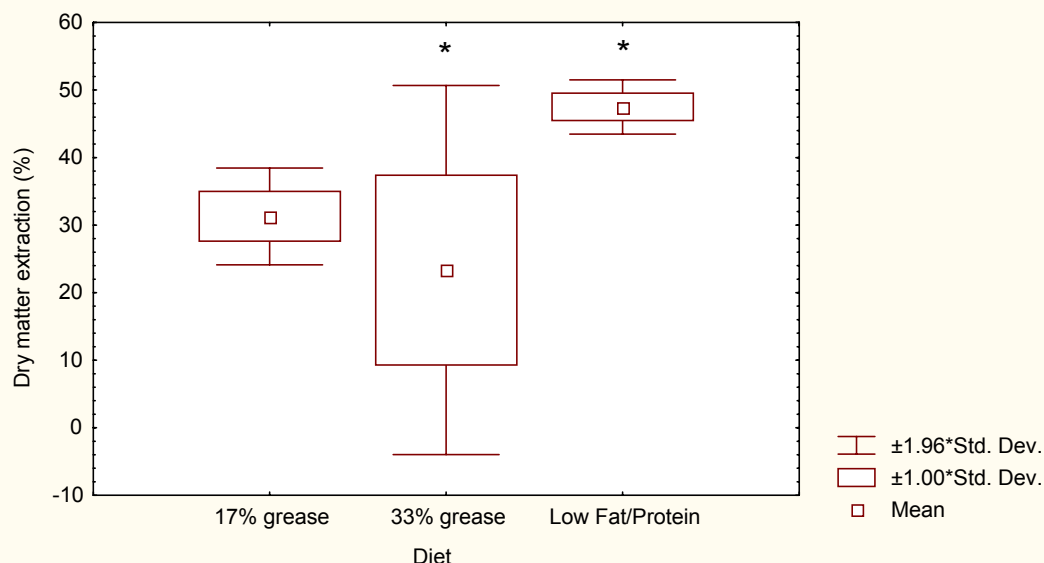
## Results: Grease Enhanced Experiment 1

Of the three diets, dry matter extraction (%) was greatest in the Low Fat/Protein Diet (one-way ANOVA,  $F = 6.43$ ,  $p = 0.03$ ) (Table 5-16). A SNK multiple range test ( $\alpha = 0.05$ ) separated the three diets into two overlapping groups, in which only the Low Fat/Protein and Low Fat/Protein with 33% grease are different from each other (Figure 5-12).

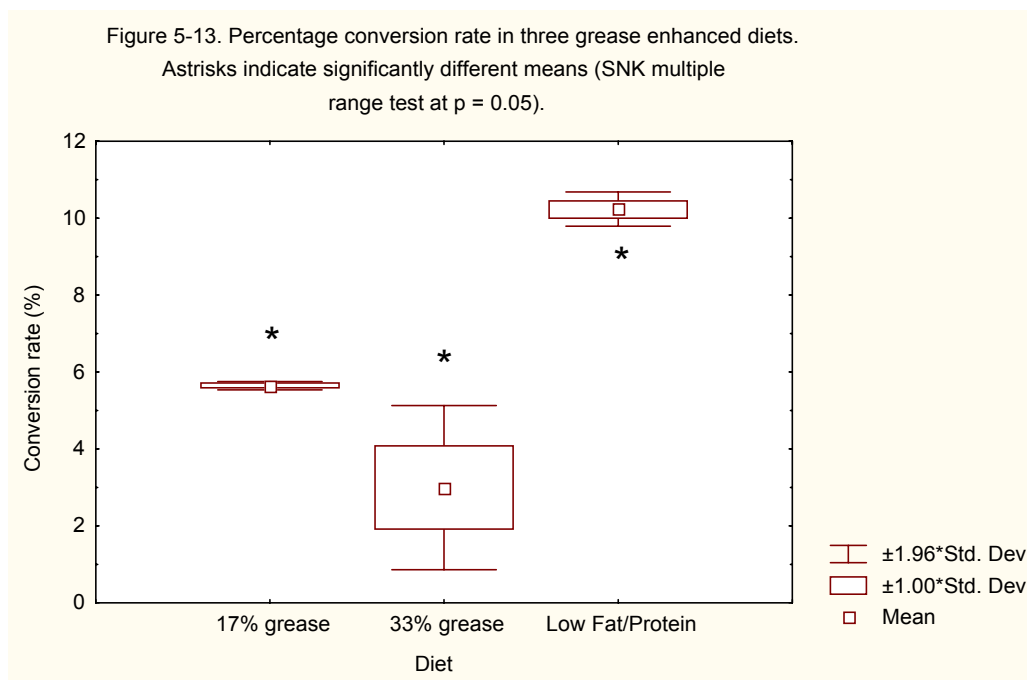
Table 5-16. Dry matter extraction, conversion rate, days to prepupae, prepupae dry matter, and prepupae wet weight of three grease enhanced diets in Grease Enhanced Diet Experiment 1. Mean and sample sizes are listed. Asterisks indicate groups with statistically different mean from SNK multiple range test ( $\alpha = 0.05$ ).

Treatment	Dry matter extraction (%)	Conversion rate (%)	Days to prepupae	Prepupae dry matter (%)	Prepupae wet weight (g)
Low Fat/Protein	47.49* (3)	10.24* (3)	23* (3)	41.01 (3)	0.20
Low Fat/Protein with 17% grease	31.28 (3)	5.65* (3)	31* (3)	50.63* (3)	0.19
Low Fat/Protein with 33% grease	23.35* (3)	3.00* (3)	31* (3)	42.19 (3)	0.26*

Figure 5-12. Percentage dry matter extraction in three grease enhanced diets.  
Asterisks indicate significantly different means by SNK multiple range test  
at  $p = 0.05$ .



The conversion rate (%) was significantly different among the three diets (one-way ANOVA,  $F = 97.40$ ,  $p < 0.001$ ). A SNK multiple range test ( $\alpha = 0.05$ ) separated the three diets into three statistically distinct groups: Low Fat/Protein with 33% Grease  $3.00 < \text{Low Fat/Protein with 17\% Grease}$   $5.65 < \text{Low Fat/Protein}$   $10.24$  (Table 5-16). This suggests that increased amounts in grease to the diet adversely affect the conversion rate (Figure 5-13).

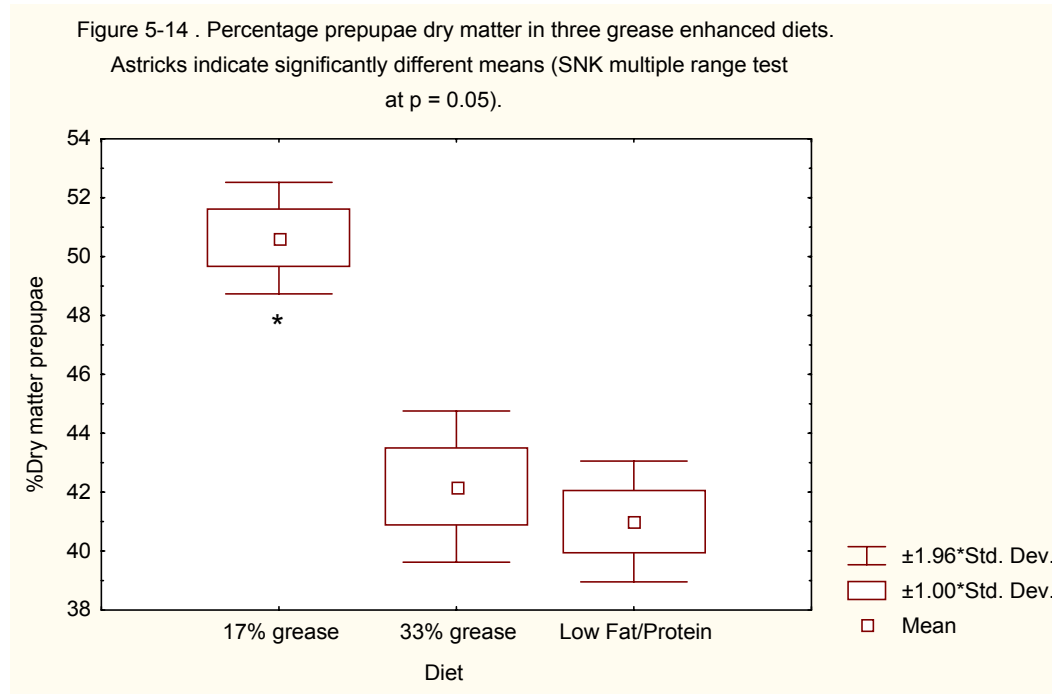


Prepupal development was faster in the Low Fat/Protein Diet, with all replication completed in 26 days, while all replications for both Low Fat/Protein with 17% and Low Fat/Protein with 33% Grease Diets took 33 and 37 days, respectively. (Table 5-16).

Mean prepupae weight (g) of the three diets was significantly different (one-way ANOVA,  $F = 24.72$ ,  $p < 0.0001$ ) (Table 5-5). A SNK multiple range test ( $\alpha = 0.05$ ) separated the means into two statistically different groups: Low Fat/Protein with 17% Grease  $0.19 =$  Low Fat/Protein  $0.20 <$  Low Fat/Protein with 33% Grease  $0.26$ .

Mean twenty prepupae dry matter (%) of the three diets was significantly different (one-way ANOVA,  $F = 66.18$ ,  $p < 0.001$ ). A SNK multiple range test ( $\alpha = 0.05$ ) separated the diets into two statistically

distinct groups: Low Fat/Protein 41.01 = Low Fat/Protein with 33% Grease 42.19 < Low Fat/Protein with 17% Grease 50.63 (Table 5-16).



The Low Fat/Protein with 33% Grease Diet had the greatest variability in each variable. This may be a result of a high grease content that was not completely absorbed, which created a hostile environmental to which the larvae were intolerant. With these extreme conditions, variability increased as larvae behavior became erratic in an attempt to survive under duress.

The Low Fat/Protein Diet had the highest dry matter extraction as the larvae consumed more diet and bioconversion was the most efficient. The Low Fat/Protein with 33% Grease Diet with the lowest dry matter

extraction may be a combination of high nutrients requiring less consumption to meet metabolic needs and less structure and surface area for larvae movement. The Low Fat/Protein with 33% Grease Diet did not have complete grease absorption and a portion of the grease floated on the surface. Larvae did not appear able to consume the liquid grease, which may account for the decreased total consumption and hence dry matter extraction.

As a result of the unabsorbed grease days to prepupae may also have been affected. Both grease enhanced diets took 31 days while the Low Fat/Protein Diet reached 20 prepupae a week earlier. Individual prepupae weight was greatest in the Low Fat/Protein with 33% Grease Diet. This may be due to a high fat content and more days in contact with the diet.

#### Grease Enhanced Diet Experiment 2

On June 5, 2003, eggs were collected from the University of Georgia at Tifton Field Station and mailed to the University of North Texas where they were placed in a 414ml plastic cup with lid (Gladware®, Oakland, CA) in a 30°C, 12L:12D photoperiod incubator. Eggs hatched on June 15, 2003. Newly hatched neonates were given Gainesville House Fly Diet. On June 23, 2003, eight-day old larvae were transferred to six 709ml plastic containers with 548 larvae in three replicates and 282 larvae in three replicates. The number of neonates was determined based on the

average number of larvae in a 1g aliquot. Table 5-17 contains the number, wet weight, diet amount, and diet-to-larvae ratio.

Table 5-17. Larval number and mean wet weights, diet applied, and grams of diet per larvae in Grease Enhanced Diet Experiment 2.

Treatment	Larvae	Larvae wet weight (g)	Diet applied (g)	Diet (g)/larvae
100% FAD	568	3.95	625.94	1.10
50% FAD	282	1.95	479.69	1.70

Two grease enhanced diet treatments were employed, each one with three replications. The treatments were: (1) 100% Fat Absorbed Diet (FAD) using Nutro's Nature Choice Lite dog food and vegetable frying oil collected from West Hall cafeteria; (2) 50% Fat Absorbed Diet (FAD) using Nutro's Nature Choice Lite dog food and vegetable frying oil collected from West Hall cafeteria.

A preliminary experiment determined the maximum grease absorbed by the bulking agent, Nutro's Nature Choice Lite dog food. This was called 100% Fat Absorbed Diet (FAD), and actually contained 27.45% vegetable frying oil, and 6 to 8.5% crude fat contained in the dog food (as indicated on the label). Therefore, the total fat content of the 100% FAD was 33.45 to 35.95% of the total weight. The 50% FAD was calculated from the absorbance experiments. It contained 13.73% grease and 6 to 8.5% crude fat contained in the dog food, for a total of 19.73 to 22.23% fat. The moisture content of the treatment was 70%, determined by calculating the gram weight of dry dog food and grease and the gram weight of water applied. Diet was added three days a week over fourteen

days on an incremental schedule for a total of 625.9g for 100% FAD and 479.7g for 50% FAD (Table 5-18).

Temperatures ranged between 29.5 and 31.12 °C in the incubator. Relative humidity ranged from 41.5 to 51.1%. Light intensity maintained a 12 hour light to 12 hour darkness periodicity with extremes ranging from 0 to 162 lumens.

Table 5-18 Diet applied (g) in Grease Enhanced Diet Experiment 2.

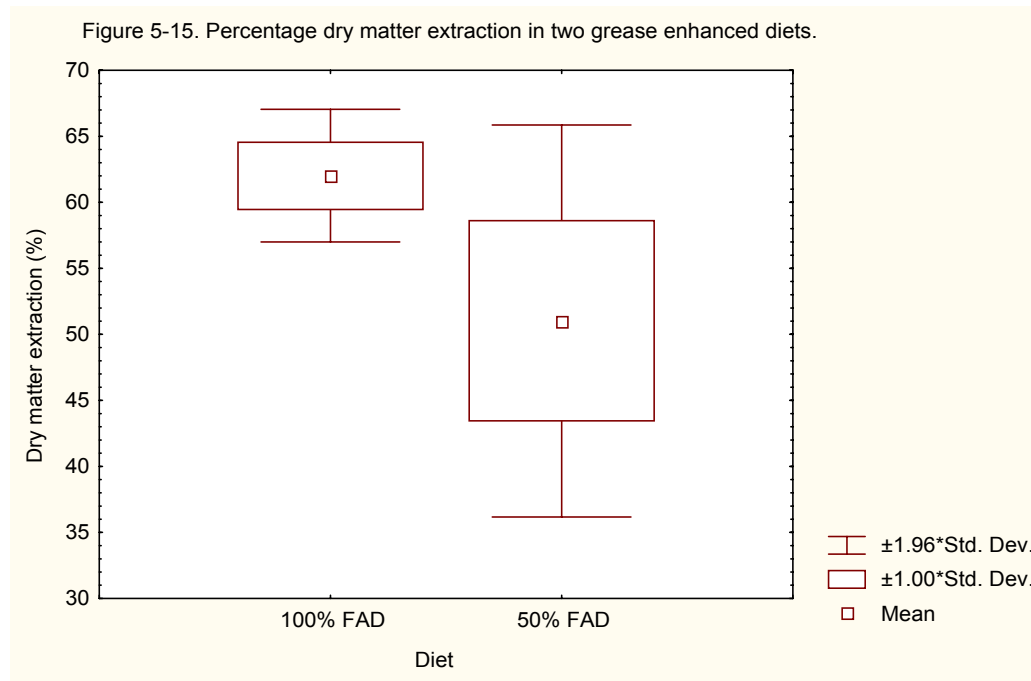
Date	100% FAD			50% FAD		
	Replicate			Replicate		
	1	2	3	1	2	3
6/24/03	138.66	138.72	138.67	61.11	60.18	60.54
6/25/03	133.62	133.16	132.43	57.49	57.32	56.53
6/26/03	108.48	109.30	109.38	120.69	120.08	120.25
7/2/03	132.86	132.14	102.95	120.80	120.92	120.58
7/7/03	121.80	123.23	122.44	121.05	121.18	120.35
Total	635.42	636.55	605.87	481.17	479.68	478.24

#### Results: Grease Enhanced Diet Experiment 2

Of the two diets, dry matter extraction (%) was greater in the 100% FAD, although not significantly different (Table 5-13). High variance in the 50% FAD treatment may have contributed to the inability to separate the means (Figure 5-15).

Table 5-19. Dry matter extraction, conversion rate, days to prepupae, prepupae dry matter, and prepupae wet weight of Grease Enhanced Diet Experiment 2. Mean and sample sizes are listed. Asterisks indicate significantly different means.

Experiment	Dry matter extraction (%)	Conversion rate (%)	Days to prepupae	Prepupae dry matter (%)	Prepupae wet weight (g)
FAD 100%	62.13 (3)	18.08* (3)	28* (3)	37.38* (3)	0.17* (60)
FAD 50%	51.01 (3)	12.14* (3)	23* (3)	38.88* (3)	0.19* (60)



Significant differences were seen in the remaining variables:

conversion rate, days to prepupae, prepupae dry matter and prepupae wet weight. While differences may be the result of diet content, several compounding variable are present. The treatments had similar diet-to-larvae ratios, but the amount of diet applied and the number of larvae

used were different. This was a result of limited larvae supply (as discussed under “Adult Colony”). Due to problems with previous experiments that used low larvae numbers per replicate, larvae were concentrated in the 100% FAD replicates, which were the focus of the experiment.

The conversion rate (%) was significantly different between the two treatments (Independent T-test,  $p = 0.002$ ), with means of 50% FAD 12.14 < 100% FAD 18.08 (Table 5-19). Mean prepupae weight (g) of the three diets was significantly different 100% FAD 0.17 < 50% FAD 0.19 (Mann Whitney U,  $p = 0.006$ ). These results are not consistent because a high conversion rate is the result of more prepupae dry matter (by weight) in relation to the amount of diet dry matter. This suggests that the prepupae weight would be higher in the 100% FAD to support a higher conversion rate. As this isn't the case, perhaps the differences in diet applied and number of larvae influenced these results.

Prepupae and residue content were analyzed for both treatments to determine if crude fat was actually consumed and if it affected prepupae composition. Crude fiber and fat content in both treatments was reduced after larval consumption. The 100% FAD had a greater percentage reduction of crude fat by approximately 30%, while the 50% FAD crude fat content was reduced by only 13% (Table 5-20). Both treatments demonstrated that larvae not only tolerate diets enhanced with vegetable grease, but consume a portion of that grease as well.

Dry matter content was increased in both treatments. The larvae certainly contributed to the drying of the diet by consumption, but also aeration through constant moving. Crude protein increased in both diets and may be a result of larval waste production.

Prepupae composition was similar between both treatments, although crude fat had the greatest difference, being 7% higher for the 100% FAD (Table 5-21); as expected, the 100% FAD produced fatter prepupae.

Table 5-20. Contents of Grease Enhanced Diet Experiment 2 pre and post consumption.

Experiment	Dry Matter (%)		Crude Protein (%)		Crude Fiber (%)		Crude Fat (%)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
FAD 100%	30	89	14	17	7	6	33-36	24
FAD 50%	30	88	14	19	7	5	19-22	19

Table 5-21. Prepupae composition after consumption in Grease Enhanced Diet Experiment 2.

Experiment	Dry Matter (%)	Crude Protein (%)	Crude Fiber (%)	Crude Fat (%)
FAD 100%	37	35	8	49
FAD 50%	39	38	9	42

## Conclusions

To reprise, the specific research objectives for the biological aspect of this project are:

- Characterize prepupae growth and development with respect to artificial diets.
- Characterize food waste reduction with respect to diet.

- Using result of this study and evaluation of the literature, determine optimum conditions for bioconversion system
- Develop a set of guidelines and criteria important in designing and managing bioconversion system for cafeteria-sized utilization potential.

Consumption of diet by black soldier fly larvae used in bioconversion seemed to be impacted by diet content. However, the optimum diet content is uncertain, as experiments in this study yielded different results.

In both Artificial Diet Experiments 1 and 2, the Low Fat/Protein and the High Fat/Protein Diets were the most successful in terms of the dry matter extracted and hence reduction of food waste. The only difference between these two experiments was the number of larvae used and the amount of diet applied.

The grams of diet per larvae impact conversion rate. Artificial Diet Experiments 1 and 2 and Grease Enhance Diet Experiments 1 and 2 used an average of 2g of diet per larvae and had conversion rates from 6 to 19%. However, the Food Waste Loading Experiment used 10 and 23g of diet per larvae and resulted in very low conversion rates of 0.40 and 0.71% (Table 5-22). With a greater diet-to-larvae ratio, the diet is not efficiently converted, suggesting that successful bioconversion should be practiced with a low ratio of diet-to-larvae to encourage larval consumption of food wastes.

Conversion rates using hen manure were lower and ranged from 1.6 to 7.8% (Sheppard and Newton 1995). The artificial diets are likely to have more useful nutrients than the manure, allowing larvae to grow larger on less diet.

Table 5-22. Mean conversion rate (%) comparisons across experiment.

	Artificial Diet Experiment 1	Artificial Diet Experiment 2	Food Waste Loading Experiment		Grease Enhanced Diet Experiment 1		Grease Enhanced Diet Experiment 2	
Low Fat/ Protein	16.61	6.40	High Loading	0.40	Low Fat/Protein	10.24	100% FAD	18.08
High Fat/ Protein	18.8	9.06	Low Loading	0.71	Low Fat/Protein with 17% Grease	5.65	50% FAD	12.14
Mix	19.53	7.66			Low Fat/Protein with 33% Grease	3.00		

Individual prepupae weight appears to be a function of diet content. The diets higher in fat/protein and grease content produced the larger prepupae (Table 5-23). The 50% FAD was an exception with larger mean larvae at 0.19g, while the 100% FAD had 0.17g larvae. Individual prepupae wet weight across the experiments ranged from 0.15 to 0.26 (Table 5-23). This is consistent with the weight of prepupae raised on hen manure, which range between 0.11 and 0.22g (Sheppard et al. 1995).

The composition of prepupae, although only determined in Grease Enhanced Experiment 2, may be compared to the results in the literature. Prepupae raised on beef manure consisted of 42% crude protein, 35% crude fat, and 7% crude fiber (Booram et al. n.d.). The Grease Enhanced Diet 2 produced prepupae with higher crude fat contents, but fiber and protein content were similar.

Table 5-23. Mean wet weight of an individual prepupae (g) comparisons across experiments.

	Artificial Diet Experiment 1	Artificial Diet Experiment 2	Food Waste Loading Experiment		Grease Enhanced Diet Experiment 1		Grease Enhanced Diet Experiment 2	
Low Fat/Protein	0.15	0.16	High Loading	0.15	Low Fat/Protein	0.20	100% FAD	0.17
High Fat/Protein	0.16	0.24	Low Loading	0.16	Low Fat/Protein with 17% Grease	0.19	50% FAD	0.19
Mix	0.19	0.20			Low Fat/Protein with 33% Grease	0.26		

The two grease enhanced diet experiments were equally inconsistent in determining the most successful diet. Grease Enhanced Diet Experiment 1 suggests that the Low Fat/Protein with no grease (hence a lower fat content) provides the best reduction and conversion rate. However, the 100% FAD in Grease Enhanced Experiment 2 had the highest conversion rate of any of the grease enhanced diets, suggesting that added fat content makes for more successful bioconversion. Of the three grease enhanced diet experiments, the 50% FAD and 100% FAD had the best outcomes, measured by dry matter extraction and conversion rate. This may be the result of a combination of greater larvae number per gram weight of food, diet moisture content, and fat content. Based on these experiments, a fat content of 33.45 to 35.95% is appropriate for a food waste diet, provided enough larvae are included and moisture content ranges between 50 and 70%.

These results indicate that larvae will consume diets with fat contents and reduce some of the fat. This is an important finding because the popular worm composting is limited to vegetative material with no oily/fatty content. Bioconverting food wastes with black soldier fly larvae increase the types of the material that can be disposed, making this system more flexible.

Given these experiments, black soldier fly larvae bioconversion is feasible with the grease enhanced Nutro Lite dog food bulking agent at 35.95% fat content. To avoid the dangers of extrapolation, future

experiments should be conducted with variable food wastes to determine their fat absorbance.

The average time frame for larvae development to prepupae on grease enhanced diets is approximately 14 to 21 days if beginning with five to seven day old larvae. None of these experiments were conducted with newly hatched larvae for practical reasons, such as difficulty handling due to small size as well as likely greater mortality with untested diets. Future experiments may want to use newly hatched larvae to determine if diets affect young larvae to a greater extent than week-old larvae. Making use of newly hatched larvae will increase the larvae-to-diet contact time, resulting in more consumption.

Prepupae dry matter did not vary drastically with diet and ranged between 35 and 50% (Table 5-24). The literature indicates that prepupae dry matter (%) generally falls around 43% (Sheppard and Newton 1995). Consistent prepupae dry matter may be due to physiological parameters of the larvae.

Table 5-24. Mean prepupae dry matter (%) comparisons across experiments.

	Artificial Diet Experiment1	Artificial Diet Experiment 2	Food Waste Loading Experiment		Grease Enhanced Diet Experiment 1		Grease Enhanced Diet Experiment 2	
Low Fat/ Protein	36.37	43.97	High Loading	41.8	Low Fat/Protein	41.01	100% FAD	39.68
High Fat/ Protein	39.58	40.38	Low Loading	39.15	Low Fat/Protein with 17% Grease	50.63	50% FAD	41.48
Mix	35.61	40.17			Low Fat/Protein with 33% Grease	42.19		

Results indicate that optimum conditions for bioconversion include a narrow range of temperature and humidity, as well as a range of suitable levels of texture, viscosity, and moisture content of the diet. Temperature should be maintained between 29 to 31°C, although significantly lower or higher temperatures were not tested and may not prove to be a problem. Relative humidity is a key condition, and should fall between 50 and 70%. Higher relative humidity, particularly with grease enhanced diets, makes the diet too wet, in which case the grease is not well absorbed into the bulking agent, resulting in a floating top layer of grease with no structure for the larvae to crawl on to get an adequate oxygen supply.

The texture of the diet should not be pureed to the degree that there is no structure to it. Without structure the larvae have a very difficult time crawling as well as consuming the food. In addition, solid grease is unlikely to provide the nutrients necessary for the larvae. The bulking agent for the grease is essential in maintaining adequate moisture, texture, and structure of the diet to optimize larval bioconversion. The feasibility of larvae consuming pure grease from kitchen grease traps was not tested, but is highly unlikely.

In designing and managing a bioconversion system, each site needs to maintain an adult colony in a greenhouse with access to full natural light throughout the year. This ensures the system has a year-round robust breeding colony. The greenhouse must be a minimum of

66m<sup>3</sup> to allow for the aerial mating process. Temperatures should range between 29 to 31°C with relative humidity between 50 and 90%. Adult females will oviposit on attractive media, thus the greenhouse needs a container with a very attractive, moist medium (e.g. Gainesville House Fly Diet) to attract egg-laying female adults.

Table 5-25. Mean dry matter extraction (%) comparisons across experiments.

	Artificial Diet Experiment1	Artificial Diet Experiment 2	Food Waste Loading Experiment		Grease Enhanced Diet Experiment 1		Grease Enhanced Diet Experiment 2	
Low Fat/ Protein	74.63	41.48	High Loading	55.54	Low Fat/Protein	47.49	100% FAD	62.13
High Fat/ Protein	52.55	35.76	Low Loading	58.64	Low Fat/Protein with 17% Grease	31.28	50% FAD	51.01
Mix	69.58	43.29			Low Fat/Protein with 33% Grease	23.35		

### Additional Considerations and Suggestions for Further Research

There are potential drawbacks of bioconversion using *H. illucens*, which should be considered. Although nothing indicates that bioconversion facilitates the spread of disease and parasites, future research should work to rule out this possibility. As larvae will be consuming food waste, which is suitable as food, it may be physiologically marginal habitat, thus leading to deleterious genetic or physiological changes (Singh 1977). The risk of changes are increased when using cultured flies with little genetic diversity over time. In addition, social stigmas and negative perceptions of flies and other arthropods may lead to confused and distracted discussion on their purposes and effectiveness (Hahn and Ascerno 1991). Complete standardized methods for employing bioconversion of food wastes that promote both resource recovery and economic profit should be finalized.

Recently, entomologists have been studying the alteration of biotic and abiotic conditions in substrates as a pest control strategy rather than applying insecticides. Moisture content, larval density, and physical and chemical properties of the insect medium are a few abiotic conditions under study as possible influences on survival, larval mass, fecundity, and behavior (e.g. predation) (Barnard and Harms 1992; Farkas et al. 1998; Jackson et al. 1998). Soil compaction, moisture content, and the interaction of the two influence the depth of pupation for some species of

fruit fly (Jackson et al. 1998; Hennessey 1994). Jackson et. al (1998) found the Mediterranean fruit fly entered dry soil to pupate, leaving it less vulnerable to predation and more protected from environmental extremes. Similarly, moisture content may influence feeding depth of *Hermetia illucens*. If feeding depth increases with moisture content, results may include decreased contact of larvae with recently applied food wastes, in turn decreasing estimated percent prepupae-to-available food waste yield. In addition, changes in feeding depth may influence larvae contact with other larvae and microbial organisms.

However, moisture content is only a single variable that could influence feeding depth behavior. Differences in behavior may be a result of medium type, density, medium temperature, relative rate of desiccation (Jackson et al. 1998; Eskafi and Fernandez 1990, Hennessey 1994), and food waste composition, age, and pH (Farkas et al. 1998). Each of these variables may influence larval survival, pupal weight, and the number of adults. Little is known about how food waste conditions affect the development of this fly species.

The conditions of other medium(s), such as poultry manure, have been studied with *H. illucens* and a wider variety of mediums for the house fly (*Musca domestica* L.) (Farkas 1998; Sheppard et al. 1995). In manure, moisture content is a particularly important factor in the control and management of the house fly. Moisture levels affect the habitability of manure by house flies (Barnard and Harms 1992; Miller et al. 1974;

Stafford and Bay 1987). At moistures levels greater than 80%, conditions become anaerobic (Barnard and Harms 1992; Miller et al. 1974; Stafford and Bay 1987), while moisture levels less than 40% in manure will not attract female house flies for oviposition (Barnard and Harms 1992; Fatchurochim et al. 1989) and will not support fly development (Barnard and Harms 1992). Sheppard (1983) found that *H. illucens* populations in poultry manure with high moisture developed more slowly.

Differences in food wastes may affect considerably the number and viability of offspring, resulting in affected efficiency of the bioconversion system using *H. illucens*. Future research should explore the rearing of *H. illucens* on a variety of food waste diets.

## APPENDIX A

### RAW DATA

Table A-1. Raw Data from Artificial Diet Experiment 1.

Treatment	LFP	LFP	LFP	HFP	HFP	HFP	Mix	Mix	Mix
Replication	1	2	3	1	2	3	1	2	3
Number of larvae	541	539	547	548	537	540	528	539	536
Diet applied (g)	633.31	633.34	633.97	633.99	632.66	634.89	633.54	632.71	634.96
Diet dry weight (g)	180.72	180.73	180.91	177.41	177.04	177.66	178.61	178.38	179.01
Diet dry matter (%)	28.54	28.54	28.54	27.98	27.98	27.98	28.19	28.19	28.19
Initial larvae wet weight(g)	5.56	5.54	5.63	5.64	1.09	1.096	1.07	1.09	1.09
Final larvae wet weight(g)	154.91	147.64	152.08	134.65	122.48	109.96	166.42	181.20	167.48
Larvae wet weight gain (g)	149.35	142.09	146.45	129.01	121.39	108.86	165.35	180.11	166.39
First prepupae observed (days)	19	19	19	18	18	17	17	18	18
20 prepupae observed (days)	21	20	21	19	18	19	19	19	19
20 prepupae wet weight (g)	3.26	2.86	3.07	3.16	2.97	3.24	3.40	3.80	3.70
20 prepupae moisture weight (g)	2.08	1.79	1.98	1.93	1.76	1.98	2.18	2.48	2.35
20 prepupae dry weight(g)	1.18	1.07	1.09	1.23	1.22	1.26	1.22	1.32	1.35
20 prepupae dry matter (%)	36.20	37.31	35.61	38.98	40.92	38.85	35.77	34.65	36.41
Residue wet weight (g)	146.15	126.62	150.66	149.90	157.62	170.99	178.11	192.26	185.94
Residue moisture weight (g)	102.66	76.75	106.40	70.40	71.82	83.80	126.25	136.93	130.06
Residue dry weight (g)	43.49	49.88	44.26	79.50	85.79	87.20	51.86	55.33	55.88
Residue dry	29.76	39.39	29.37	53.04	54.43	50.99	29.12	28.78	30.05

matter (%)									
Diet reduction (g)	487.16	506.71	483.31	484.09	475.04	463.89	455.43	440.45	449.02
Diet reduction (%)	76.92	80.00	76.24	76.36	75.09	73.07	71.89	69.61	70.72
Dry matter extraction (%)	75.94	72.41	75.54	55.19	51.54	50.92	70.97	68.98	68.79
Conversion rate (%)	17.63	15.93	16.27	18.76	18.52	19.12	18.38	19.92	20.30

Table A-2. Raw Data from Artificial Diet Experiment 2.

Treatment	LFP	LFP	LFP	HFP	HFP	HFP	Mix	Mix	Mix
Replication	1	2	3	1	2	3	1	2	3
Number of larvae	100	100	100	100	100	100	100	100	100
Diet applied (g)	383.61	382.35	383.11	381.54	382.52	382.34	381.36	381.90	383.06
Diet dry weight (g)	109.32	109.12	109.32	106.77	107.04	106.99	108.82	108.98	109.31
Diet dry matter (%)	28.54	28.54	28.54	27.98	27.98	27.98	28.54	28.54	28.54
Initial larvae wet weight(g)	0.38	0.38	0.29	0.35	0.38	0.41	0.40	0.37	0.35
Final larvae wet weight(g)	25.95	9.93	22.62	26.60	27.60	25.22	39.81	38.57	29.61
Larvae wet weight gain (g)	25.57	9.54	22.34	26.19	27.22	24.87	39.41	38.14	29.25
First prepupae Observed (days)	16	18	15	15	15	15	15	15	15
20 prepupae observed (days)	26	10prepupae in 31 days	26	22	22	22	23	23	23
20 prepupae wet weight (g)	3.18	1.30*	3.81	4.70	4.91	4.75	4.04	4.21	4.21
20 prepupae moisture weight(g)	1.82	0.70*	2.17	2.83	2.94	2.81	2.41	2.51	2.53
20 prepupae dry weight(g)	1.37	0.60*	1.64	1.87	2.01	1.93	1.62	1.71	1.68
20 prepupae dry matter (%)	42.94	45.99	42.97	39.81	40.58	40.74	40.17	40.39	39.96
Residue wet weight(g)	64.18	80.02	63.02	102.97	114.57	98.70	66.63	67.78	76.64
Residue moisture weight (g)	4.95	5.48	4.99	34.16	45.58	30.43	7.322	7.03	10.90
Residue dry weight (g)	59.23	74.54	58.03	68.81	68.99	68.27	59.31	60.75	65.74
Residue dry matter (%)	92.29	93.15	92.08	66.83	60.22	69.17	89.01	89.63	85.78

Diet reduction (g)	319.43	302.33	320.09	278.57	267.95	283.64	314.73	314.12	306.42
Diet reduction (%)	83.27	79.07	83.55	73.01	70.05	74.19	82.53	82.25	79.99
Dry matter extraction (%)	45.82	31.69	46.92	35.55	35.55	36.19	45.50	44.50	39.86
Conversion rate (%)	6.25	5.47	7.49	8.77	9.37	9.04	7.45	7.83	7.70

Table A-3. Raw Data for Food Waste Loading Experiment.

Treatment	Low Loading	Low Loading	Low Loading	High Loading	High Loading	High Loading
Replication	1	2	3	1	2	3
Number of larvae	45	45	45	46	45	45
Diet applied (g)	450	450	450	1050	1050	1050
Diet dry wt (g)	243.54	243.54	243.54	568.26	568.26	568.26
Diet dry matter (%)	54.12	54.12	54.12	54.12	54.12	54.12
Initial larvae wet weight(g)	4.48	5.09	4.97	4.42	4.91	4.10
Final prepupae/larvae wet weight (g)	5.99	7.49	6.62	7.04	6.41	7.04
Larvae wet weight gain (g)	1.51	2.40	1.21	2.62	1.50	2.94
30 prepupae wet weight (g)	4.37	4.72	4.09	4.78	4.60	4.91
30 prepupae moisture weight (g)	2.67	2.88	2.47	2.79	2.66	2.87
30 prepupae dry weight (g)	1.70	1.83	1.62	1.99	1.94	2.04
30 prepupae dry matter (%)	38.94	38.86	39.65	41.66	42.24	41.50
Residue wet weight (g)	224.86	225.56	212.76	522.31	544.21	515.15
Residue moisture weight (g)	129.69	120.79	110.50	268.98	289.41	265.32
Residue dry weight (g)	95.17	104.77	102.26	253.32	254.80	249.83
Residue dry matter (%)	42.32	46.45	48.06	48.5	46.82	48.50
Diet reduction (g)	225.14	224.44	237.24	527.70	505.79	534.85
Diet reduction (%)	50.03	49.87	52.72	50.26	48.17	50.94
Dry matter extraction (%)	60.92	56.98	58.01	55.42	55.16	56.04
Conversion rate (%)	0.70	0.75	0.67	0.35	0.34	0.51
Prepupae/Larvae Found	38	44	43	42	41	42
Survival %	91.30	84.40	91.10	93.30	97.80	95.60

Table A1-4. Raw Data from fat absorbance experiment with bulking agent.

Treatment	Weigh boat (g)	Dog food (g)	Grease (g)	Absorbed Grease (g)	% Grease	Water Added (g)	Total weight (g)	% Moisture
1	9.84	10.01	10.05	3.57	26.30	32.00	45.58	70.20
2	10.12	10.30	15.06	3.23	23.90	32.45	45.98	70.50
3	10.08	10.21	20.10	4.38	30.00	34.23	48.82	70.10
4	10.45	10.02	25.12	4.29	29.60	33.05	47.35	69.80
Average		10.14		3.87	27.45	32.93	46.93	70.15

Table A-5. Raw Data for Grease Enhanced Diet Experiment 1.

Treatment	Low Fat/Protein	Low Fat/Protein	Low Fat/Protein	Low Fat/Protein with 17% grease	Low Fat/Protein with 17% grease	Low Fat/Protein with 17% grease	Low Fat/Protein with 33% grease	Low Fat/Protein with 33% grease	Low Fat/Protein with 33% grease
Replication	1	2	3	1	2	3	1	2	3
Number of larvae	123	123	123	123	123	123	123	123	123
Diet Applied (g)	401.40	401.02	401.26	479.80	482.45	481.30	551.46	552.88	552.01
Diet dry weight (g)	120.42	120.31	120.38	201.52	202.63	202.15	292.27	293.03	292.56
Diet dry matter (%)	30.00	30.00	30.00	42.00	42.00	42.00	53.00	53.00	53.00
Initial larvae wet weight (g)	8.651	8.58	8.63	8.64	8.67	8.61	8.61	8.60	8.35
Final prepupae/larvae wet weight (g)	30.49	32.49	27.57	22.73	22.60	21.25	20.41	25.42	12.54
Larvae wet weight gain (g)	21.84	23.90	18.94	14.10	13.93	12.64	11.80	16.82	4.20
20 prepupae observed (days)	26	26	26	33	33	33	37	37	37
20 prepupae wet weight (g)	4.24	4.16	3.57	3.67	3.94	3.28	3.95	3.17	3.93
20 prepupae moisture weight(g)	2.55	2.38	2.10	1.85	1.94	1.59	2.34	1.824	2.22
20 prepupae dry weight(g)	1.69	1.75	1.46	1.82	2.00	1.69	1.61	1.341	1.70
20 prepupae dry matter (%)	39.94	42.03	41.05	49.60	50.76	51.52	40.80	42.37	43.40
Larvae dry weight (g)	9.02	10.17	8.56	6.52	5.28	7.19	7.46	10.48	3.74

Larvae dry matter (%)	38.51	38.14	38.69	52.16	51.29	55.27	45.29	47.08	43.35
Remaining prepupae dry weight (g)	1.36	0.69	0.79	3.16	4.11	2.45	N/A	N/A	N/A
Remaining prepupae dry matter (%)	48.19	41.60	41.96	48.18	49.16	49.48	N/A	N/A	N/A
Larvae & prepupae dry weight (g)	12.08	12.61	12.28	11.50	11.39	11.34	9.07	11.82	5.44
Residue wet weight (g)	133.16	134.83	138.03	161.13	171.89	166.812	380.24	383.90	389.72
Residue moisture weight (g)	68.97	74.46	72.97	14.14	36.91	32.18	124.62	144.88	211.49
Residue dry weight (g)	64.19	60.37	65.06	146.99	134.98	134.64	255.62	239.02	178.23
Residue dry matter (%)	48.21	44.77	47.13	91.22	78.53	80.71	67.23	62.26	45.73
Diet reduction (g)	268.24	266.19	263.23	318.68	310.55	314.48	171.22	168.98	162.29
Diet reduction (%)	66.83	66.38	65.60	66.42	64.40	65.34	31.05	30.56	29.40
Dry matter extraction (%)	46.69	49.82	45.96	27.06	33.38	33.40	12.54	18.43	39.08
Conversion rate (%)	10.03	10.48	10.20	5.71	5.62	5.61	3.10	4.03	1.86

Table A-6. Raw Data for Grease Enhanced Diet Experiment 2.

Treatment	100% FAD	100% FAD	100% FAD	100% FAD	50% FAD	50% FAD	50% FAD	50% FAD
Replication	1	2	3	Mean	1	2	3	Mean
Number of larvae	568	568	568	568	282	282	282	282
Diet applied (g)	635.42	636.55	605.87	625.94	481.17	479.68	478.24	479.70
Diet dry weight (g)	196.53	197.71	166.98	187.07	142.91	141.87	141.32	142.03
Diet dry matter (%)	30.93	31.06	27.56	29.85	29.70	29.58	29.55	29.61
Initial larvae wet weight(g)	3.95	3.95	3.94	3.95	1.96	1.96	1.931	1.95
Final prepupae/larvae wet weight (g)	80.06	77.06	75.07	77.40	40.13	41.99	39.40	40.51
Larvae wet weight gain (g)	76.11	73.12	71.13	73.45	38.16	40.04	37.47	38.56
20 prepupae observed (days)	28	28	28	28	23	22	23	22.67
20 prepupae wet weight (g)	3.69	3.32	3.27	3.43	4.03	3.83	3.63	3.83
20 prepupae moisture weight(g)	2.20	2.00	1.99	2.07	2.36	2.23	2.14	2.24
20 prepupae dry weight(g)	1.49	1.32	1.28	1.36	1.67	1.61	1.50	1.59
20 prepupae dry matter (%)	40.38	39.71	38.94	39.68	41.35	41.92	41.16	41.48
Prepupae/Larvae dry weight (g)	32.89	32.30	31.69	32.29	15.50	16.17	15.28	15.65
Prepupae/Larvae dry matter (%)	43.06	43.80	44.13	43.66	42.95	42.38	42.70	42.68
Larvae & prepupae dry weight (g)	34.37	33.62	32.96	33.65	17.17	17.78	16.77	17.24
Residue wet weight (g)	76.89	82.97	74.89	78.25	68.69	65.57	68.62	67.63
Residue moisture weight (g)	7.64	7.73	7.56	7.64	5.21	5.60	5.30	5.37
Residue dry weight (g)	69.25	75.24	67.33	70.61	63.48	59.97	63.32	62.26
Residue dry matter (%)	90.06	90.68	89.91	90.22	92.42	91.46	92.28	92.05
Diet reduction (g)	558.52	553.58	530.98	547.69	412.48	414.11	409.62	412.07

Diet reduction (%)	87.90	86.97	87.64	87.50	85.72	86.33	85.65	85.90
Dry matter extraction (%)	64.76	61.94	59.68	62.13	55.58	42.27	55.19	51.01
Conversion rate (%)	17.49	17.00	19.74	18.09	12.01	12.53	11.87	12.14

## APPENDIX B

### STATISTICAL ANALYSIS RESULTS

Table B-1. Results of Artificial Diet Experiments 1 and 2. Asterisks indicate statistically significant diets.

Variable	Experiment Number	Diet	N	X	SD	Shapiro-Wilk (p)	ANOVA F, (p)
Diet wet weight applied (g)	1	Low Fat/Protein	3	633.54	0.37	0.07	Not sig.
		High Fat/Protein	3	633.85	1.12	0.78	
		Mix	3	633.74	1.14	0.72	
	2	Low Fat/Protein	3	383.02	0.63	0.77	Not sig.
		High Fat/Protein	3	382.13	0.52	0.33	
		Mix	3	382.10	0.87	0.60	
Residue wet weight (g)	1	Low Fat/Protein	3	141.14	12.77	0.34	13.61 0.006
		High Fat/Protein	3	159.50	10.67	0.71	
		Mix*	3	185.43	7.09	0.88	
	2	Low Fat/Protein	3	69.07	9.50	0.12	20.40 0.002
		High Fat/Protein*	3	105.41	8.21	0.50	
		Mix	3	70.35	5.48	0.20	
Residue moisture (g)	1	Low Fat/Protein	3	95.27	16.14	0.23	20.86 0.002
		High Fat/Protein	3	75.33	7.35	0.19	
		Mix*	3	131.07	5.41	0.69	
	2	Low Fat/Protein	3	5.14	0.29	0.13	40.49 0.0003
		High Fat/Protein*	3	36.72	7.89	0.46	
		Mix	3	8.42	2.16	0.13	
Residue dry weight (g)	1	Low Fat/Protein*	3	45.87	3.48	0.21	107.93 <0.0001
		High Fat/Protein*	3	84.16	4.10	0.33	
		Mix*	3	54.35	2.17	0.24	
	2	Low Fat/Protein	3	63.93	9.21	0.12	Not sig.
		High Fat/Protein	3	68.69	0.37	0.46	
		Mix	3	61.93	3.38	0.41	
Mass reduction wet weight (g)	1	Low Fat/Protein	3	492.39	12.55	0.29	13.98 0.006
		High Fat/Protein	3	472.34	10.12	0.89	
		Mix*	3	448.30	7.512	0.84	
	2	Low Fat/Protein	3	313.95	10.07	0.063	21.01 0.002
		High Fat/Protein*	3	276.72	8.01	0.62	

		Mix	3	311.75	4.63	0.13	
Mass reduction (%)	1	Low Fat/Protein	3	77.72	2.01	0.33	13.73 0.006
		High Fat/Protein	3	74.84	1.66	0.75	
		Mix*	3	70.74	1.14	0.97	
	2	Low Fat/Protein	3	81.97	2.51	0.11	20.60 0.002
		High Fat/Protein*	3	72.42	2.13	0.53	
		Mix	3	81.59	1.39	0.19	
Individual prepupae wet weight (g)	1	Low Fat/Protein	60	0.15	0.02	0.13	44.24 0.0001
		High Fat/Protein	60	0.16	0.02	0.78	
		Mix*	60	0.19	0.02	0.49	
	2	Low Fat/Protein	50	0.17	0.03	0.01	Kruskall-Wallis Table A3-2
		High Fat/Protein	60	0.24	0.03	0.85	
		Mix	60	0.21	0.02	0.01	
20 prepupae wet weight (g)	1	Low Fat/Protein	3	3.06	0.20	0.95	8.61 0.017
		High Fat/Protein	3	3.12	0.14	0.53	
		Mix*	3	3.63	0.21	0.47	
	2	Low Fat/Protein*	3	3.20	0.61	0.96	14.76 0.005
		High Fat/Protein	3	4.79	0.11	0.39	
		Mix	3	4.15	0.10	<0.0001	
20 prepupae moisture (g)	1	Low Fat/Protein	3	1.94	0.15	0.70	9.35 0.014
		High Fat/Protein	3	1.88	0.12	0.41	
		Mix*	3	2.33	0.15	0.87	
	2	Low Fat/Protein*	3	1.80	0.39	0.92	16.65 0.004
		High Fat/Protein	3	2.86	0.07	0.24	
		Mix	3	2.48	0.06	0.28	
20 prepupae dry weight (g)	1	Low Fat/Protein*	3	1.11	0.06	0.42	8.81 0.016
		High Fat/Protein	3	1.23	0.02	0.79	
		Mix	3	1.29	0.07	0.42	
	2	Low Fat/Protein* (different from High Fat/Protein)	3	1.40	0.22	0.75	11.57 0.009

		High Fat/Protein* (different from Low Fat/Protein)	3	1.94	0.07	0.93	
		Mix	3	1.67	0.04	0.52	
Initial larvae wet weight (g)	1	Low Fat/Protein	3	5.58	0.05	0.37	Kruskall-Wallis Table A3-2
		High Fat/Protein	3	2.61	2.63	0.002	
		Mix	3	1.08	0.01	0.20	
	2	Low Fat/Protein	3	0.35	0.05	0.09	Not sig.
		High Fat/Protein	3	0.38	0.03	0.96	
		Mix	3	0.37	0.02	0.52	
Dry matter extraction (%)	1	Low Fat/Protein*	3	74.63	1.93	0.20	114.53 <0.0001
		High Fat/Protein*	3	52.55	2.31	0.26	
		Mix*	3	69.58	1.21	0.15	
	2	Low Fat/Protein	3	41.48	8.49	0.12	1.71 0.259
		High Fat/Protein	3	35.76	0.37	<0.0001	
		Mix	3	43.29	3.01	0.32	
Conversion rate (%)	1	Low Fat/Protein*	3	16.61	0.90	0.36	10.76 0.010
		High Fat/Protein	3	18.80	0.30	0.78	
		Mix	3	19.53	1.02	0.36	
	2	Low Fat/Protein*	3	6.40	1.02	0.75	13.64 0.006
		High Fat/Protein*	3	9.06	0.30	0.89	
		Mix*	3	7.66	0.19	0.66	
Dry matter prepupae (%)	1	Low Fat/Protein*	3	36.37	0.87	0.66	13.91 0.006
		High Fat/Protein	3	39.58	1.16	0.11	
		Mix	3	35.61	0.89	0.71	
	2	Low Fat/Protein*	3	43.97	1.76	0.01	12.16 0.008
		High Fat/Protein	3	40.38	0.50	0.31	
		Mix	3	40.17	0.21	0.99	
Final larvae wet weight (g)	1	Low Fat/Protein*	3	151.54	3.67	0.76	23.68 0.001
		High Fat/Protein*	3	122.36	12.35	0.98	
		Mix*	3	171.70	8.24	0.12	

Larvae wet weight gain (g)	2	Low Fat/Protein* (different from Mix)	3	19.50	8.46	0.38	5.94 0.038
		High Fat/Protein	3	26.47	1.20	0.83	
		Mix* (different from Low Fat/Protein)	3	35.99	5.57	0.21	
	1	Low Fat/Protein*	3	145.96	3.65	0.78	31.53 0.001
		High Fat/Protein*	3	119.75	10.17	0.73	
		Mix*	3	170.62	8.24	0.12	
	2	Low Fat/Protein* (different from Mix)	3	19.15	8.48	0.37	5.91 0.038
		HFP	3	26.09	1.1	0.86	
		Mix* (different from Low Fat/Protein)	3	35.60	5.53	0.22	

Table B-2. Non-parametric results of Artificial Diet Experiments 1 and 2. Asterisks indicate statistically significant diets.

Variable	Exp. #	Diet	N	Min.	Q <sub>1</sub>	Median	Q <sub>3</sub>	Max.	Shapiro-Wilk (p)	Kruskall-Wallis (p)
First prepupae observed (days)	1	Low Fat/Protein*	3	19	19	19	19	19	----	0.046
		High Fat/Protein	3	17	17	18	18	18	<0.0001	
		Mix	3	17	17	18	18	18	<0.0001	
	2	Low Fat/Protein	3	15	15	16	18	18	0.637	Not sig.
		High Fat/Protein	3	15	15	15	15	15	--	
		Mix	3	15	15	15	15	15	--	
Twenty prepupae observed (days)	1	Low Fat/Protein*	3	20	20	21	21	21	<0.0001	0.034
		High Fat/Protein	3	18	18	19	19	19	<0.0001	
		Mix	3	19	19	19	19	19	----	
	2	Low Fat/Protein*	3	19	19	19	24	24	<0.0001	0.020
		High Fat/Protein*	3	15	15	15	15	15	--	
		Mix*	3	16	16	16	16	16	--	
Initial larvae wet weight (g)	1	Low Fat/Protein	3	5.54	5.54	5.56	5.63	5.63	0.369	Not sig.
		High Fat/Protein	3	1.09	1.09	1.09	5.64	5.64	0.002	
		Mix	3	1.07	1.07	1.08	1.08	1.08	0.202	
Individual prepupae wet weight (g)	2	Low Fat/Protein*	50	0.10	0.14	0.16	0.20	0.21	0.013	<0.0001
		High Fat/Protein*	60	0.17	0.22	0.24	0.26	0.30	0.847	

		Mix*	60	0.17	0.19	0.20	0.22	0.26	0.009	
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Table B-3. Results of assumption test for Artificial Diet Experiments 1 and 2.

Variable	Experiment Number	n	S <sup>2</sup>			Critical Value	F <sub>max</sub>
			Low Fat/Protein	High Fat/Protein	Mix		
Diet applied wet weight (g)	1	3	0.139	1.260	1.290	87.50	9.28
	2	3	0.400	0.274	0.756	87.50	2.76
Residue wet weight (g)	1	3	163.193	113.943	50.250	87.50	3.25
	2	3				87.50	
Mass reduction wet weight (g)	1	3	157.464	102.406	56.525	87.50	2.79
	2	3	101.355	64.097	21.442	87.50	4.43
Initial larvae wet weight (g)	1	3	0.002	6.904	0.0001	87.50	69040.00
	2	3	0.002	0.001	0.001	87.50	5.07
Final larvae wet weight (g)	1	3	13.440	152.471	67.968	87.50	11.34
	2	3	71.498	1.431	30.985	87.50	49.94
Larvae wet weight gain (g)	1	3	13.334	103.480	67.858	87.50	7.76
	2	3	71.837	1.391	30.619	87.50	51.63
Individual prepupae wet weight (g)	1	60	0.0004	0.0004	0.001	1.85	1.09
	2	60	0.001	0.001	0.0004	1.85	2.08
Residue moisture (g)	1	3	260.795	54.129	29.327	87.50	8.89
	2	3	0.086	62.308	4.644	87.50	719.41
Residue dry weight (g)	1	3	12.160	16.819	4.745	87.50	3.54
	2	3	84.752	0.140	11.391	87.50	603.65
Twenty prepupae wet weight (g)	1	3	0.041	0.019	0.043	87.50	2.28
	2	3	0.368	0.012	0.010	87.50	35.30
Twenty prepupae moisture (g)	1	3	0.021	0.014	0.022	87.50	1.62
	2	3	0.148	0.004	0.003	87.50	38.91
	1	3	0.004	0.0004	0.005	87.50	11.50

Twenty prepupae dry weight (g)	1	3	0.004	0.0004	0.005	87.50	11.50
Twenty prepupae dry weight (g)	2	3	0.059	0.006	0.001	87.50	25.33
Dry matter extraction (%)	2	3	3.081	0.2457	0.046	87.50	67.26
Dry matter extraction (%)	1	3	3.736	5.323	1.458	87.50	3.65
Conversion Rate (%)	2	3	72.137	0.137	9.057	87.50	528.47
Conversion Rate (%)	1	3	0.809	0.091	1.034	87.50	11.33
Wet weight reduction (%)	2	3	1.038	0.090	0.037	87.50	27.82
Wet weight reduction (%)	1	3	4.019	2.751	1.293	87.50	3.11
Wet weight reduction (%)	2	3	6.302	4.544	1.936	87.50	3.26

Table B-4. Results of Food Waste Loading Experiment.

Variable	Diet	N	X	SD	Shapiro-Wilk (p)	T-test (p)
Residue wet weight (g)	Low Loading	3	221.06	7.20	0.093	<0.001
	High Loading	3	527.22	15.14	0.456	
Residue moisture (g)	Low Loading	3	120.33	9.60	0.920	<0.001
	High Loading	3	274.57	12.98	0.270	
Residue dry weight (g)	Low Loading	3	100.73	4.98	0.487	<0.001
	High Loading	3	252.65	2.56	0.560	
Mass reduction wet weight (g)	Low Loading	3	228.94	7.20	0.093	<0.001
	High Loading	3	522.78	15.14	0.456	
Individual prepupae wet weight (g)	Low Loading	90	0.15	0.04	<0.0001	<0.074
	High Loading	90	0.16	0.05	<0.0001	
30 prepupae wet weight (g)	Low Loading	3	4.39	0.31	0.884	0.142
	High Loading	3	4.76	0.16	0.795	
30 prepupae moisture (g)	Low Loading	3	2.67	0.22	0.960	

	High Loading	3	2.77	0.12	0.730	
30 prepupae dry weight (g)	Low Loading *	3	1.72	0.11	0.735	0.016
	High Loading *	3	1.99	0.05	0.942	
Initial larvae wet weight (g)	Low Loading	3	4.85	0.33	0.347	0.289
	High Loading	3	4.48	0.41	0.763	
Final larvae wet weight (g)	Low Loading	3	6.70	0.76	0.823	0.802
	High Loading	3	6.83	0.36	0.003	
Larvae wet weight gain (g)	Low Loading	3	1.71	0.62	0.471	0.317
	High Loading	3	2.35	0.76	0.405	
Dry matter prepupae (%)	Low Loading	3	39.48	0.56	0.501	0.055
	High Loading	3	41.80	0.39	0.395	
Dry matter extraction (%)	Low Loading	3	58.64	2.04	0.487	0.062
	High Loading	3	55.54	0.45	0.557	
Conversion rate (%)	Low Loading	3	0.71	0.04	0.726	0.007
	High Loading	3	0.40	0.10	0.100	
Wet weight reduction (%)	Low Loading	3	50.87	1.60	0.096	0.433
	High Loading	3	49.79	1.44	0.454	

Table B-5. Non-parametric results of Food Waste Loading Experiment.

Variable	Exp. #	Diet	N	Min.	Q <sub>1</sub>	Median	Q <sub>3</sub>	Max.	Shapiro-Wilk (p)	Kruskall-Wallis (p)
Larvae/Prepupae Found	1	Low Loading	3	38	38	43	44	44	0.298	0.507
		High Loading	3	41	41	41	42	42	<0.0001	
Individual prepupae wet weight (g)	1	Low Loading	90	0.10	0.12	0.14	0.17	0.29	<0.0001	0.231
		High Loading	90	0.09	0.13	0.14	0.18	0.28	<0.0001	

Table B-6. Results of assumption test for Food Waste Loading Experiment.

Variable	n	S <sup>2</sup>		F Test F, p
		Low Loading	High Loading	
Initial larvae wet weight (g)	3	0.107	0.168	1.57 0.777
Final larvae wet weight (g)	3	0.574	0.130	4.40 0.370
Larvae wet weight gain (g)	3	0.387	0.571	1.48 0.808
Individual prepupae wet weight (g)	90	0.001	0.002	1.69 0.014
30 prepupae wet weight (g)	3	0.098	0.024	4.05 0.396
30 prepupae moisture (g)	3	0.043	0.002	3.65 0.430
30 prepupae dry weight (g)	3	0.011	0.002	5.02 0.332
Residue wet weight (g)	3	51.786	229.316	4.43 0.369
Residue dry weight (g)	3	24.777	6.529	3.80 0.417
Residue moisture (g)	3	92.197	168.518	1.83 0.707
Wet weight mass reduction (g)	3	51.786	229.316	4.43 0.369
Dry matter prepupae (%)	3	0.312	0.152	2.06 0.653
Dry matter extraction (%)	3	4.175	0.204	20.43 0.093
Conversion rate (%)	3	0.002	0.009	5.57 0.304
Wet weight reduction (%)	3	2.564	2.084	1.23 0.897

Table B-7. Results of Grease Enhanced Diet Experiments 1 and 2. Asterisks indicate statistically significant diets.

Variable	Experiment Number	Diet	N	X	SD	Shapiro-Wilk (p)	ANOVA F, (p)
Diet wet weight applied (g)	1	Low Fat/Protein*	3	401.23	0.19	0.732	22228.10 <0.0001
		Low Fat/Protein with 17% Grease*	3	481.18	1.33	0.853	
		Low Fat/Protein with 33% Grease*	3	552.12	0.72	0.753	
	2	50% FAD*	3	479.69	1.47	0.981	F= 140.99 0.0014 0.0045
		100% FAD*	3	625.94	17.39	0.062	
Dry Matter Diet (g)	1	Low Fat/Protein *	3	120.37	0.06	0.701	145220.00 <0.0001
		Low Fat/Protein with 17% Grease *	3	202.10	0.56	0.851	
		Low Fat/Protein with 33% Grease *	3	292.62	0.38	0.740	
	2	50% FAD*	3	142.03	0.81	0.666	F= 464.94 0.004 0.046
		100% FAD*	3	187.07	17.41	0.064	
Residue wet weight (g)	1	Low Fat/Protein *	3	135.34	0.89	0.657	2861.07 <0.0001
		Low Fat/Protein with 17% Grease *	3	166.61	5.39	0.936	
		Low Fat/Protein with 33% Grease *	3	384.62	4.78	0.750	
	2	50% FAD*	3	67.63	1.78	0.036	F= 5.58 0.304 0.016
		100% FAD*	3	78.25	4.21	0.458	
Residue moisture (g)	1	Low Fat/Protein	3	72.13	2.84	0.507	18.48
		Low Fat/Protein with 17% Grease	3	27.74	12.02	0.378	0.003

		Low Fat/Protein with 33% Grease *	3	160.33	45.45	0.429	F= 5.76 0.296 <0.0001
	2	50% FAD*	3	5.37	0.20	0.424	
		100% FAD*	3	7.64	0.09	0.935	
Residue dry weight (g)	1	Low Fat/Protein *	3	63.21	2.49	0.332	34.07 0.005
		Low Fat/Protein with 17% Grease *	3	138.87	7.03	0.046	
		Low Fat/Protein with 33% Grease *	3	224.29	40.74	0.391	
	2	50% FAD*	3	62.26	1.98	0.076	F= 41.73 0.047 0.003
		100% FAD*	3	70.61	4.12	0.448	
Mass reduction wet weight (g)	1	Low Fat/Protein *	3	265.89	2.52	0.798	1136.73 <0.0001
		Low Fat/Protein with 17% Grease *	3	314.57	4.06	0.963	
		Low Fat/Protein with 33% Grease *	3	167.5	4.65	0.465	
	2	50% FAD	3	412.07	2.27	0.700	
	3	100% FAD	3	547.69	14.69	0.323	
Individual prepupae wet weight (g)	1	Low Fat/Protein	60	0.20	0.05	0.355	24.72 <0.0001  K-W <0.0001
		Low Fat/Protein with 17% Grease	60	0.19	0.05	0.514	
		Low Fat/Protein with 33% Grease *	43	0.26	0.01	0.139	
	2	50% FAD*	60	0.19	0.04	<0.0001	K-W 0.006
		100% FAD*	60	0.17	0.02	0.102	
20 prepupae wet weight (g)	1	Low Fat/Protein	3	3.99	0.37	0.221	0.76 0.509
		Low Fat/Protein with 17% Grease	3	3.63	0.33	0.810	
		Low Fat/Protein with 33% Grease	3	3.68	0.45	0.042	

	2	50% FAD	3	3.83	0.20	1.00	F= 1.32 0.864 0.083
		100% FAD	3	3.43	0.22	0.209	
20 prepupae moisture weight (g)	1	Low Fat/Protein	3	2.34	0.23	0.731	4.40 0.067
		Low Fat/Protein with 17% Grease	3	1.80	0.18	0.482	
		Low Fat/Protein with 33% Grease	3	2.13	0.27	0.404	
	2	50% FAD	3	2.24	0.12	0.800	F= 1.15 0.932 0.127
		100% FAD	3	2.06	0.11	0.081	
20 prepupae dry weight (g)	1	Low Fat/Protein	3	1.48	0.15	0.338	2.36 0.175
		Low Fat/Protein with 17% Grease	3	1.84	0.16	0.805	
		Low Fat/Protein with 33% Grease	3	1.55	0.19	0.477	
	2	50% FAD*	3	1.59	0.09	0.679	F= 1.67 0.748 0.048
		100% FAD*	3	1.36	0.11	0.344	
Initial larvae wet weight (g)	1	Low Fat/Protein	3	8.62	0.03	0.678	1.54 0.288
		Low Fat/Protein with 17% Grease	3	8.64	0.03	0.842	
		Low Fat/Protein with 33% Grease	3	8.52	0.148	0.070	
	2	50% FAD*	3	1.95	0.02	<0.0001	K-W 0.04
		100% FAD*	3	3.95	0.006	<0.0001	
Final larvae wet weight (g)	1	Low Fat/Protein * (Diff. From 33% only)	3	30.18	2.47	0.793	5.71 0.041
		Low Fat/Protein with 17% Grease	3	22.19	0.82	0.155	

		Low Fat/Protein with 33% Grease * (Diff. From Low Fat/Protein only)	3	19.46	6.49	0.756	
	2	50% FAD*	3	40.51	1.34	0.529	F= 3.54 0.441 <0.0001
		100% FAD*	3	77.40	2.51	0.778	
Larvae wet weight gain (g)	1	Low Fat/Protein *	3	21.56	2.49	0.815	5.83 0.039
		Low Fat/Protein with 17% Grease	3	13.56	0.80	0.197	
		Low Fat/Protein with 33% Grease	3	10.94	6.36	0.775	
	2	50% FAD*	3	38.56	1.33	0.501	F= 3.55 0.439 <0.0001
		100% FAD*	3	73.45	2.51	0.780	
Total larvae/prepupae dry weight (g)	1	Low Fat/Protein	3	12.32	0.27	0.738	2.96 0.128
		Low Fat/Protein with 17% Grease	3	11.41	0.08	0.658	
		Low Fat/Protein with 33% Grease	3	8.78	3.20	0.848	
	2	50% FAD	3	17.24	0.51	0.772	F= 1.92 0.203 0.074
		100% FAD	3	33.65	0.71	0.925	
Dry matter extraction (%)	1	Low Fat/Protein **	3	47.49	2.05	0.342	6.43 0.032
		Low Fat/Protein with 17% Grease	3	31.28	3.66	0.005	
		Low Fat/Protein with 33% Grease **	3	23.35	13.94	0.407	
	2	50% FAD*	3	51.01	7.57	0.049	F= 8.86 0.203 0.074
		100% FAD*	3	62.13	2.55	0.879	
Conversion rate (%)	1	Low Fat/Protein *	3	10.24	0.23	0.732	97.40

		Low Fat/Protein with 17% Grease *	3	5.65	0.06	0.174	<0.001
		Low Fat/Protein with 33% Grease *	3	3.00	1.09	0.843	
	2	50% FAD*	3	12.14	0.35	0.387	F= 17.65 0.107 0.002
		100% FAD*	3	18.08	1.46	0.322	
Dry matter prepupae (%)	1	Low Fat/Protein	3	41.01	1.05	0.931	66.18 <0.001
		Low Fat/Protein with 17% Grease *	3	50.63	0.97	0.771	
		Low Fat/Protein with 33% Grease	3	42.19	1.31	0.772	
	2	50% FAD*	3	41.81	0.42	0.559	F= 3.00 0.500 0.011
		100% FAD*	3	39.68	0.72	0.924	
Wet weight reduction (%)	1	Low Fat/Protein	3	66.27	0.62	0.707	1777.44 <0.001
		Low Fat/Protein with 17% Grease	3	365.39	1.01	0.924	
		Low Fat/Protein with 33% Grease *	3	30.34	0.85	0.560	
	2	50% FAD	3	85.90	0.37	0.179	F= 249.68 0.008 0.285
		100% FAD	3	90.84	5.91	0.150	
Days to 20 prepupae	1	Low Fat/Protein*	3	26	0	--	<0.0001
		Low Fat/Protein with 17% Grease*	3	33	0	--	
		Low Fat/Protein with 33% Grease*	3	37	0	--	
	2	50% FAD*	3	23	0.58	<0.0001	K-W 0.034
		100% FAD*	3	28	0	--	

Table B-8. Results of assumption test for Grease Enhanced Diet Experiment 1.

Variable	n	S <sup>2</sup>			Critical Value	F <sub>max</sub>
		Low Fat/Protein	Low Fat/Protein with 17% grease	Low Fat/Protein with 33% grease		
Diet applied wet weight (g)	3	0.036	1.758	0.513	87.50	48.83
Dry matter diet (g)	3	0.003	0.310	0.147	87.50	99.97
Residue wet weight (g)	3	6.111	29.019	22.878	87.50	4.75
Mass reduction wet weight (g)	3	6.338	16.506	21.601	87.50	3.41
Initial larvae wet weight (g)	3	0.001	0.001	0.022	87.50	27.83
Final larvae wet weight (g)	3	6.108	0.672	42.134	87.50	62.67
Larvae wet weight gain (g)	3	6.203	0.637	40.410	87.50	63.39
Individual prepupae wet weight (g)	3	0.002	0.002	0.003	2.40	1.35
Residue moisture weight (g)	3	8.060	144.381	2065.805	87.50	256.30
Residue dry weight (g)	3	6.218	49.436	1660.033	87.50	15003.91
Twenty prepupae wet weight (g)	3	0.135	0.111	0.198	87.50	1.79
Twenty prepupae moisture (g)	3	0.050	0.033	0.072	87.50	2.18
Twenty prepupae dry weight (g)	3	0.023	0.024	0.035	87.50	1.56
Total larvae/prepupae dry weight (g)	3	0.072	0.007	10.240	87.50	1440.23
Dry matter extraction (%)	3	4.205	13.356	194.248	87.50	46.20
Conversion rate (%)	3	0.052	0.003	1.185	87.50	395.07

Dry matter prepupae (%)	3	1.093	0.935	1.714	87.50	1.83
Wet weight reduction (%)	3	0.387	1.022	0.718	87.50	2.64

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