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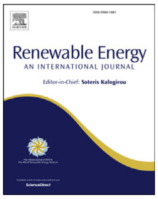

Bioconversion of organic wastes into biodiesel and animal feed via insect farming

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A B S T R A C T

Approximately one-third of all food produced for human consumption worldwide is wasted. The current waste management practices are not only costly but also have adverse impact on environment. In this study, black soldier fly (BSF) (*Hermetia illucens*) larvae were grown on food wastes to produce fat and protein-rich BSF prepupae as a novel strategy for efficient organic waste management. The lipid content in BSF prepupae was characterized for fatty acids profile. Whole BSF prepupae, pressed cake, and meal were analyzed for important animal feed characteristics. BSF-derived oil has high concentration of medium chain saturated fatty acids (67% total fatty acids) and low concentration of polyunsaturated fatty acids (13% total fatty acids), which makes it potentially an ideal substrate for producing high quality biodiesel. BSF (prepupae, pressed cake, and meal) has feed value comparable to commercial feed sources. Thus, the bioconversion of organic waste into BSF prepupae has significant potential in generating high-value products with simultaneous waste valorization.

1. Introduction

Meeting an ever increasing demand for the food, feed, and fuel and managing waste, especially the organic waste, has become a major global challenge. The situation is projected to be aggravated with the rapidly increasing global population, which is estimated to increase from 7.3 billion in 2015 to 9.7 billion in 2050 [1]. Currently, about one-third of food produced, which is equivalent to 1.3 billion metric tons is wasted or lost and has significant environmental (i.e., greenhouse gas (GHGs) emissions) and economic footprints [2]. For example, in India alone, the postharvest loss of agricultural produce is estimated to be about 92 million tons (Mton) per year [3]. Without considering the land use change, the annual GHGs emissions equivalent of food wastage is estimated to be 3.3 billion metric tons of CO_2 equivalent GHGs [2]. Similarly, the economic footprint of the food produced but not consumed accounts for the loss of nearly $750 billion per year [2]. Additionally, waste management, especially in developing and underdeveloped countries, has become a serious issue. The management of organic wastes, among different wastes, is more challenging due to its bulky nature and rapid degradability [4]. The current organic wastes management practices, namely land fill and waste treatment/stabilization via anaerobic digestion and composting to meet environmental regulations, are not only costly but also have adverse impacts on environment such as ground and surface water contaminations and GHGs emissions among others [4,5].

On the other hand, both rapid increase in global population and associated affluence are believed to have caused significant increase in demand for food, feed, and fuel, and waste generation [5]. For example, global energy demand is estimated to increase from 524 Quadrillion Btu (QBtu) in 2010 to 820 QBtu by 2040, a 56% increase compared to 2010 [6]. Similarly, the global demands for food and animal products are projected to increase by 70–100% [7] and 50–70% [8], respectively, by 2050. To cope up with the demand for animal products, a substantial increase in nutritious animal feedstuffs is needed. On one hand, the production of conventional feedstuffs such as soybean meal is reported as the major

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contributor to land occupation, climate change, and water and energy consumption [9,10]. Additionally, such conventional animal feedstuffs are not only limited in supply but also are becoming more expensive over the years. On the other hand, the growing concern of climate change, which is expected to bring extreme climate variability (e.g., long drought, heavy winter storm, and occurrence of frequent floods among others), the situation is likely to aggravate further the food security situation due to its impact on agriculture-based food and feed production systems [11]. Moreover, there is already a strong competition for resources such as food, feed, and biofuel productions, and the competition is projected to be even fiercer with increased demand for food, feed, and fuel. Thus, there is a pressing need for identifying and exploring the potential of alternative non-conventional sources of food, feed, and fuel, which are economically viable, environmentally friendly, and socially acceptable.

The black soldier fly (BSF) (*Hermetia illucens*), a detritivorous insect belonging to order Diptera and family Stratiomyidae, is native to tropical, subtropical, and warm temperate zone of America [12]. The insect is now distributed, due to global trade and business, in tropical to warm temperate regions in Europe [13], North [14] and South America, Australia [15], and Asia [16,17]. Due to its widespread distribution and ease with which it can be maintained in a colony [14], there is substantial global interest in the mass production of the BSF as a means to produce protein [15].

The BSF lifecycle consists of four stages, namely; egg, larvae, pupae, and adult. Adults typically mate for two days after emergence [18]. Females lay a single clutch of eggs for two days after mating [18] and resulting eggs hatch in approximately four days [12]. Within natural environments (e.g., livestock operations), eggs are deposited in cracks and crevices near to food sources [19]. Larvae pass through five instars. Larvae are quite omnivorous, as they feed on a variety of materials ranging from animal [20] and human feces [21], kitchen waste [22] to vertebrate remains (e.g., decomposing swine carcasses) [23]. Depending on the size of the larvae, type of the substrate available, and environmental conditions (e.g., moisture, temperature, and air supply), the larvae consume from 25 to 500 mg of organic matter per larva per day [24]. Similarly, depending on the substrate type, the larvae are reported to reduce the waste by about 39% (pig manure) [25] and 50% (chicken manure) [26] to 68% (municipal organic waste) [27] and have a food conversion ratio (FCR) of about 10 to 15 [25–27]. The larval stage is usually 14 days or longer depending on availability of food [12], and appropriate environmental conditions [28,29]. During the later larval stage; the stage prior to pupation termed as prepupae [26], larvae get rid of their digestive track and migrate away from their food sources in search of dry and protected place to pupate [26]. Since adults are non-feeding, BSF larvae consume organic matter as much as possible and store fat and protein in their body to support their metabolism during pupal and adult stages [25]. By using a specially designed bioreactor, the typical migrating behavior of prepupae can be exploited for self-harvesting of prepupae [26] for extracting fat and protein for value-added products generation. The pupation stage usually lasts for two weeks under ideal environmental conditions [12,30,31].

In the context of growing demand for food, feed, and fuel, as well as a need for managing organic wastes, the use of insect, to efficiently convert organic wastes into fuel, food, and feed appears to be innovative and promising. Thus, this study aims to farm a unique insect, the BSF on such organic waste as a novel strategy in managing organic wastes and producing high-value fat- and protein-rich insect biomass. Thereafter, the produced fat- and protein-rich insect biomass, in downstream processing, can be fractionated into fat (i.e., raw material for biodiesel production) and protein-rich insect meal (for animal feed applications). The specific objectives of this study were to (i) characterize fatty acids profile of the insect fat as a potential substrate for biodiesel production, and (ii) analyze the proximate composition and amino acids profile of insect biomass and defatted insect cake and meal for animal feed application.

2. Materials and methods

2.1. Black soldier fly rearing and oil extraction

BSF was grown in the food wastes collected from school cafeteria (Clemson University, Clemson, SC USA and Pearl City High School, Honolulu, HI USA) by using specially designed reactor for self-harvesting of prepupae. The schematic of bioconversion of food waste to biofuel and animal feed is presented in Fig. 1. Harvested larvae were dried using conveyer oven (Despatch Oven Co., Minneapolis, MN USA) at 60 °C to the moisture content of around 5–8%. The dried BSF prepupae grown in Clemson University and Pearl City High School were mixed to make a composite sample. The mixed dried BSF prepupae were fractionated into crude oil and cake/meal using both mechanical and chemical means. Mechanical extraction was conducted using a lab-scale Taby Press Type 20 (Skeppsta Maskin AB, Sweden). The extracted crude oil was collected, centrifuged, and the mass of the supernatant oil was recorded. The pressed cake following mechanical extraction was further chemically extracted using a Soxhlet apparatus (Ace Glass Incorporated, NJ USA) for four hours using petroleum ether as a solvent. Afterwards, solvent was removed using a rotary evaporator (Buchi, Flawil, Switzerland) at 50 °C. BSF prepupae, pressed cake, and pressed and solvent extracted meal (termed as “meal” hereafter) were sent to the Department of Aquatic Feeds and Nutrition at the Oceanic Institute (Waimanalo, HI, USA) for complete characterization (i.e. fatty acids composition and nutritional profile).

2.2. Analytical methods

The nutritional profile of the BSF prepupae, pressed cake, and meal were characterized following the Association of Official Analytical Chemists (AOAC) standard procedures [32] with specific methods as follows: dry matter (DM) (oven drying at 105 °C to constant weight), ash (ignition at 550 °C in an electric furnace, AOAC 942.05), crude fiber (AOAC 962.09), crude protein by determining N by dry combustion using LECO analyzer (LECO FP-528 Nitrogen determiner, Leco Corp., St. Joseph, MI) (AOAC 976.05, crude protein $= N \times 6.25$), crude lipid (AOAC 920.39), and carbohydrate by subtracting the crude protein, crude lipid and ash contents from total dry matter. Gross energy content was determined using an oxygen bomb calorimeter (Parr Bomb Calorimeter 6200, Parr Instrument Co., Moline, IL). Amino acids (both essential and non-essential) was determined using High Performance Liquid Chromatography (Agilent 1200, Agilent Technologies Inc., Santa Clara, CA) using AOAC method no 982.30 E (a,b,c). Fatty acids including EPA and DHA were analyzed using a gas chromatograph (Varian 3800 GC; Varian Analytical Instrument, Walnut Creek, CA) equipped with a flame ionization detector (AOAC 996.06). During fatty acid profile analysis, the C12:0 in BSF prepupae derived oil was determined by assigning the peak before C14:0 as a peak for C12:0 based on literature review [33–35].

2.3. Statistical analyses

The experiments and sample analyses for all important parameters discussed above were performed in triplicates. The statistical analysis was conducted using Statistical Analysis System (SAS) software (SAS 9.2, SAS Institute Inc., Cary, NC USA). The