An Agroecological Future: Perennial Kernza and Black Soldier Flies for Food and Feed

by

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ABSTRACT

Global food production faces significant challenges, including climate change, depletion of resources, loss of biodiversity, food waste, environmental pollution, among others. Addressing these challenges requires adopting a multifaceted approach. Thus, the objectives of this study were to: (i) determine the performance and nutrient composition of BSFL reared on two underexplored waste streams from sustainable crop production (kernza straw and spent mushroom (*L. edodes*) substrate) and two widely available waste streams (spent coffee grounds and mixed institutional food waste), while replicating real-world environmental growing conditions; (ii) develop a framework for evaluating the kernza in context education curriculum of The Land Institute using principles of agroecology and using feedback from the curriculum developers on the evaluation tool to enhance the evaluation curriculum. After 12 days of the experiment (chapter two), larvae fed kernza-supplemented diets showed the best growth and feed efficiency, while those fed food waste had the highest fat and dry matter but lower protein and fiber. Larvae fed both diets (food waste and kernza-supplemented diets) significantly reduced waste compared to others. Overall, BSFL proved effective in converting various waste materials into valuable biomass, offering a potential pathway for valorizing waste and an alternative to soybean feed in the livestock industry. In the second study (chapter three), a framework was developed to evaluate the kernza curriculum using the principles of agroecological education. Using five principles: hands-on learning, a broad and interdisciplinary approach, communication, inclusion, and peer learning, I evaluated a lesson on grains. After developing an evaluation framework and using it to evaluate the lessons in the curriculum, there was a feedback process where I walked through the evaluation framework with the curriculum developers and implemented their feedback to further enhance the lessons. Overall, this study underscores the importance of integrating agroecological principles in addressing real-world problems.

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Chapter One: General Introduction

One of the key contributors to consumption-related environmental impact in the United States is food production. Producing food requires key resources such as land, water, energy, and raw materials. Between 2007 and 2016, about 21-37% of the anthropogenic greenhouse gas emissions resulted from food production, agriculture, forestry, and other land use activities (IPCC, 2019). Livestock production causes environmental emissions in the form of methane during the process of enteric fermentation of ruminants, while manure runoff and storage causes ground and surface water pollution and impacts on the environment. In crop production, fertilizer application causes direct emission of N_2O from soil processes. When fertilizer is applied to the soil, ammonia and N_2O is released through a process called denitrification, contributing to eutrophication and acidification of waterways. Global food production will become more unpredictable and increasingly difficult as a result of climate change (Garnett, 2014). In 2022, agriculture contributed about 10.% of the total anthropogenic greenhouse gas emissions in the United States (EPA, 2024). The impact of greenhouse gases caused by food production is projected to increase as the demand for food increases (O'Mara, 2011). The negative environmental consequences of food production are further worsened when food is wasted.

Food waste refers to any leftover food from cooking that is uneaten, whether it is from homes or businesses (EPA, 2008). Food waste is not just an environmental problem but an economic and social problem. Every year, about 30-50% of the food produced for humans worldwide (Gustavsson *et al.,* 2011), an equivalent of 1.3 billion metric tons is wasted (FAO, 2011), which has a significant environmental (3.3 billion metric tons of CO2-equivalent greenhouse gas (GHG) emission per year) and economic (total social costs of $ 1.2 trillion per year) footprints (FAO, 2014). In developed countries like the United States for example, most of the food waste is generated by consumers (House of Lords European Union Committee, 2014). The United Nations Food and Agriculture Organization estimated the per capita food waste generation in Europe and North America to be 95-115 kg/year (FAO, 2014). In the United States, more food is found in municipal landfills than any other material, making up about 24% of municipal solid waste in 2018 (EPA, 2020). Municipal solid waste and urban food waste is projected to increase by 51 and 44%, respectively, from 2005 to 2025 (Adhikari *et al.,* 2006). If the current solid waste management policies are maintained, food waste landfills in urbans areas are estimated to increase from 8% to 10% (Adhikari *et al.,* 2009). When food is wasted, resources such as land, water, energy, and labor that goes into producing that food – from farm to table – is also wasted (WRAP, 2009; European Commission, 2010; FAO, 2014).

Despite increasing awareness and effort to manage and reduce food waste, the vast majority still ends up in landfills, causing significant problems in our environment. Several studies have reported a growing interest in and awareness of managing and recovering food waste in the Unites States and other parts of the world (Pearson *et al.,* 2013; Platt *et al.,* 2014; Neff *et al.,* 2015). However, very little food waste is being recovered to-date (EPA, 2014) and little has been done to prevent it. There are many negative environmental effects of food waste depending on how it is managed. When wasted food is sent to landfills, it breaks down to release methane, a greenhouse gas that has the potential to cause global warming 25 times more than carbon dioxide on a 100-year time scale (IPCC, 2007). In a report for CleanMetrics authored by Venkat (2011), about 123 MMT CO2e (million metric tons of carbon dioxide equivalent) are added to the atmosphere from the production, transportation, and disposal of wasted food. In landfills, methane has the tendency to breakdown faster than other organic waste materials, releasing high amounts of methane, and contributes only small amounts of carbon sequestered in landfills (Levis and Barlaz, 2011).

On the other hand, conventional crop production constitutes a great source of environmental pollution. Over reliance of conventional agriculture on synthetic pesticides and fertilizers tremendously impact on the environment and public health. In the United States, it is estimated that the impact of environmental and healthcare cost of pesticides application are about $10 billion per year (Pimentel, 2005). Furthermore, over 90% of corn farmers in the United States rely on herbicides for weed control (Pimentel *et al.,* 1993), with Atrazine, one of the most widely used herbicides in corn, the most commonly found pesticide in streams and groundwater (USGS, 2001). In addition, fertilizer and animal manure-nutrient loss causes deterioration and loss of aquatic habitat in North America (Frankenberger and Turco 2003). In the Gulf of Mexico, run-off of soil and nitrogen fertilizer from the corn belt has contributed to the anaerobic 'dead zone'. A 2003 report by the United States' National Academy of Sciences puts that the cost of wasted fertilizer from excess fertilizer input is about $2.5 billion (National Academy of Sciences, 2003). Modern agricultural practices like tillage also causes soil erosion. A study by Pimentel *et al.* (1995) estimated the cost of public and environmental health losses related to soil erosion to be over $45 billion every year. All these underscores the urgent need for more sustainable agricultural practices to mitigate the negative impact of conventional agriculture.

Efforts to divert food waste from landfills in the United States have led to the development of various strategies, programs, and policies at both local and state levels. As far back as 2004, a nationwide survey by Simmons *et al.* (2006) estimated there were 7,689 curbside recycling programs in the United States that served approximately 82 million people. These numbers may have been underestimated because 18 states did not respond to the survey used to collect this data. In other food waste recycling surveys conducted in 2008, it was found that about 273 facilities currently accepted food waste (Olivares and Goldstein, 2008; Olivares *et al.,* 2008). Another strategy that has been employed to divert food waste from landfills is to treat more waste biologically through aerobic composting or anaerobic digestion. While these waste management practices have made significant strides, they still face challenges related to long-term sustainability and efficiency.

In light of the challenges of global food production and challenges of waste management, researchers have been working on ways to address these problems. One of such is a new waste valorization process that is feasible and economically and environmentally sustainable. One of these proposed waste management strategies is the use of insects to decompose food and organic waste.

Edible insects have been gaining attention all over the world because of their potential use in animal feed, excellent ability to convert organic and food waste materials into nutrient-rich biomass, and potential to increase farm efficiency and sustainability (Govorushko, 2019; De Souza-Vilela *et al.,* 2019, Fukuda *et al.,* 2022). They have smaller environmental footprint compared to beef cattle and pork production (Oonincx *et al.,* 2010) and use only 0.2% total land compared to 99% of land use in conventional system (Oonincx and De Boer 2012), decrease the potential of global warming by 61%, and lower energy use by 38 (Van Zanten *et al.,* 2015). The black soldier fly (*Hermatia illucens)* is one of such insects that decomposes waste, recover nutrients from waste, and generates income (Sheppard *et al.,* 1994).

The black soldier fly (*Hermatia illucens*) (BSF) is considered a beneficial non-pest. They do not bite or sting and are not known to transmit any disease. They secrete harmful substances that make it difficult for houseflies to breed and diminish food borne pathogens such as

Escherichia coli and *Salmonella enterica* (Amrul *et al.,* 2022). As such, there is little concern about disease transmission between animals and from animals to humans due to large scale composting with BSF larvae (BSFL). Newton *et al*, (1977) reported that the larvae contain natural antibiotics which act on growth promoter in animal feed. They are usually found around decaying materials and are also capable of dealing with extreme environmental conditions like drought, food shortage, and oxygen deficiency (Dienner *et al.,* 2011) and the larvae decompose organic material faster than worms used in vermicomposting (Rindhe *et al.,* 2019). Compared to other composting techniques, composting with BSF requires cost-effective, requires low maintenance, are less sophisticated and easy to operate, has low land requirements, and has low ecological footprints while offering more economical potential (Singh and Kumari, 2019).

BSFL feed on organic waste materials and efficiently break them down, gaining nutrient rich body biomass that can be used as different livestock feed, as well as producing biodiesel and chitin in the process (Van Huis *et al.,* 2013; Diener *et al.,* 2011; Li *et al.,* 2015). A recent review, Amrul *et al.* (2022) found that several researchers have used BSFL to reduce different types of waste materials, including food and vegetable waste, animal manure, human feces, etc. In their study, Diener *et al.* (2011) reported that BSFL are able to reduce 65-78% waste. In addition, the frass of BSFL, a by-product of decomposition contains substantial amount of nutrients (Lalander *et al.,* 2015; Oonincx *et al.,* 2015) and could be used as an organic fertilizerin crop production. Furthermore, in addition to the production of by-products that are economically beneficial, composting with BSFL is environmentally sustainable. Song *et al.* (2021) reported that composting with BSFL lowers global warming potential compared to waste management using incineration. Additionally, Mertenat *et al.* (2019) demonstrated that when the same waste stream is used, composting with BSFL generated less than 2.5% of the GHG emissions of that generated in windrow composting. Thus, showing the multiple benefits this method of composting can offer.

On the other hand, as climate change threatens the world and environmental degradation occurring as a result of industrial agriculture dominated by annual cropping, perennial cropping systems have been proposed as a useful strategy to make agriculture adapted to the ever-changing climate because they have extended growing season and provide continuous ground cover, helping them to sequester more soil carbon and reduce nutrient leaking (Crews, 2005; Chimento and Amaducci, 2015). Compared to annuals, perennial crops can provide a more ecosystem function such as provisioning (gain and biomass production), regulating (pest and weed suppression, soil erosion control, carbon sequestration, water regulation), supporting (soil fertility enhancement, biodiversity) among others (Picasso *et al.,* 2008). Perennials can also help improve food security and address problems of soil erosion and water pollution (Chapman *et al.,* 2022; Glover *et al.,* 2010). One such novel perennial crop is intermediate wheatgrass (*Thinopyrun intermedium*) also known as kernza, developed by The Land Institute, in Salina, Kansas, U.S.A., under the branded name Kernza®. Kernza is the first commercially available perennial grain and is a cool season pasture. Similar to wheat, kernza has large seeds. It also has a high-water use efficiency throughout its growing season, which helps it mitigate water stress, a physiological characteristic that helps it adapt under extreme weather conditions (De Olivera *et al.,* 2020). Furthermore, several studies have shown that kernza grown for grain has the potential protect rural drinking water sources by reducing NO_3 leaching in groundwater (Huddell *et al.,* 2023; Jungers *et al.,* 2019; Reilly *et. al.,* 2022). As a result of these important traits, research has been ongoing to develop this novel crop with ability to produce agroecological benefits that can counteract the effect of climate change and reverse environmental degradation.

Kernza embodies agroecology and its principles because of its multiple benefits and applicability. Thus, educating future professionals on perennials like kernza is important because it teaches them about sustainable agriculture and agroecological benefits perennial crops like kernza offers. Agroecology is a sustainable agricultural practice that takes into consideration the biological, environmental, economic, and social dimensions of agriculture. Thus, valorizing waste with BSFL and evaluating sustainable agriculture curriculum to include principles of agroecological education can help address problems of global food production and concerns relating to waste management. This approach connects education and applied science and shows how both solutions can help address problems caused by conventional agriculture. Together, these approaches provide a holistic approach to promoting sustainable practices and equipping future professionals with the tools to tackle multidimensional agricultural challenges.

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Chapter Two: Performance and Nutrient Composition of Black Soldier Fly Larvae Fed Food and Crop Wastes

Abstract

Black soldier fly larvae (BSFL) are recognized for their efficiency in converting organic waste materials into nutrient-rich body mass, which is a useful feed ingredient for chickens, pigs, and salmonids. This pilot study investigated the performance and nutrient composition of larvae grown on food and crop waste streams. Five-day old larvae were reared on five diets: 100% chicken feed as the control; 100% mixed food waste from campus dining; 80% chicken feed + 20% spent mushroom substrate; 80% chicken feed + 20% spent coffee grounds; and 80% chicken feed + 20% kernza straw. After a 12-day feeding period, larvae fed kernza-supplemented diets had the highest average body weight (0.12 g) and lowest feed conversion ratio, which differed significantly from larvae fed food waste. However, significantly more waste was reduced in the mixed food waste and kernza-supplemented diets compared to other diets. Mortality rate ranged from 6 to 16% and did not differ significantly among treatments. Larvae fed food waste had the highest dry matter (37%) and fat (34%) content, and lowest crude protein (46%), crude fiber (5.2%), calcium (0.6%, and phosphorus (0.9%) content compared to other treatments. Although performance and nutrient composition were generally poorest on 100% mixed food waste, larvae were nonetheless able to grow on and reduce all experimental waste streams, indicating the potential of using BSFL to valorize these materials. In particular, kernza straw shows promise as a novel and sustainable feed substrate for BSFL bioconversion.

Introduction

Food waste is a primary driver of anthropogenic greenhouse gas (GHG) emissions (Amicarelli *et al.* 2021). About one third of the food produced globally is wasted, totaling approximately 1.3 billion tons of food each year, worth around 1 trillion USD (WFP, 2020). In the United States, between 30% and 40% of all food is wasted (USDA, 2023) representing the single largest category of materials found in municipal landfills, where it generates methane in the process of anaerobic decomposition. Methane, a GHG, is a particular concern for climate change, as it is about 86 times more potent than carbon dioxide (IPCC, 2013). The United Nations and United States have both set goals to reduce 50% of global food waste by 2030 through prevention, reduction, recycling, and reuse (EPA, 2015; United Nations, 2015). Finding opportunities to divert waste from landfills is important to meet these goals.

Animal production is another important driver of climate change, producing approximately 7.1 million tons of CO_2 equivalent each year, representing between 14-17.3% of human-induced GHG emissions (Xu *et al.,* 2021). Livestock require a significant amount of arable land for fodder production, and the type of feed largely determines its impact on the environment (Ilea 2009). Protein supplements, one of the most expensive and limiting feed ingredients in livestock production, rely heavily on resource-intensive soybean production (Molden, 2013; Rockström *et al.,* 2009; WWF, 2024). Climate change, dwindling of arable land and water, high energy costs, shifting dietary demands, and other pressures threaten the future supply of these feed resources (Alexandratos and Bruinsma, 2012). Consequently, researchers are exploring non-conventional animal feedstuff to replace or supplement conventional sources.

Production of black soldier flies (BSF) (*Hermetia illucens*) could simultaneously address waste management and animal feed challenges. As natural decomposers in ecosystems, BSF larvae (BSFL) can convert a wide range of organic wastes like fecal sludge, animal manure, spent brewers' grains, agricultural waste, fruit and vegetable waste, and slaughterhouse waste into nutrient-dense body mass (Li *et al.,* 2020; Tschirner *et al.,* 2015). BSFL have been widely recognized as a safe and healthy feed ingredient for poultry, swine, and salmonids and have been approved for use in several countries (Alagappan *et al.,* 2022). Although the composition of food waste varies depending on the food consumed, geographic region, and season (Li *et al.,* 2021), studies have shown that BSFL can grow on a diet of 100% mixed food waste from restaurants or households (Nyakeri *et al.,* 2017). Other waste streams may not be suitable as the sole diet but can be used as supplements. For example, spent coffee grounds are a suboptimal feed for BSFL growth and development, but are suitable when blended with other ingredients (Khaekratoke *et al.,* 2022; Fischer *et al.,* 2021).

Mixed food waste and spent coffee grounds are abundant, easily accessible waste streams that typically end up in landfills (Forcina *et al.,* 2023), making them ideal candidates for valorization through BSFL production. However, many other potential feed substrates remain underexplored. In particular, the growing markets for more sustainable food crops generate novel byproducts that could be recycled and valorized through BSFL, further promoting sustainable agriculture. For example, perennial grain crops can provide beneficial ecosystem services and alleviate some of the environmental issues caused by reliance on annual crops. Kernza (*Thinopyrum intermedium*), a perennial grain crop, is touted for its ability to provide ecosystem services such as sequestering carbon, building soil organic matter, reducing soil erosion, improving water infiltration, and providing food and forage (Crews, 2021). Its grain can be processed into baked goods and beers (Marti *et al.,* 2016), while its forage (straw, hay) is suitable for use as a low-quality additive in livestock rations (Favre *et al.,* 2019; Hunter *et al.,* 2020; The

Land Institute, 2021). However, no studies to the best of our knowledge have explored whether kernza straw, the crop residue remaining after grain harvest, could be fed to BSFL to produce enriched biomass for livestock feed.

Mushrooms are another environmentally friendly crop as they require few resources to produce (Pandey *et al.,* 2018; Rosmiza *et al.,* 2016). However, the process of growing mushrooms generates ample spent mushroom substrate. Spent mushroom substrate is rich in organic matter and contains about 75-85% of unused nutrients (Moon *et al.,* 2012). Its composition depends on the substrate medium, and species used, among other factors (Wei *et al.,* 2017 Given the rapid growth in mushroom cultivation and consumer demand worldwide, there is a need to find sustainable uses for spent mushroom substrate (Atallah *et al.,* 2021; Grimm *et al.,* 2021). In their study, Cai *et. al.* (2017) fed BSFL a mixed diet of kitchen waste or wheat bran with mushroom (*F. velutipes*) roots and reported an increase in the feed conversion rate of BSFL by 31.2-172.7% and decrease in developing time by 16-16 days. Another study conducted by Li *et al.* (2021) fed four different mushroom varieties (*Auricularia heimuer, Lentinus edodes, Pleurotus eryngii and Pleurotus citrinopileatus)* to determine their potential as feed materials for BSFL. The study reported that BSFL fed mushroom substrate at different supplementation ratios with food waste (0-90%) had survival rate of 99.2-100%. Importantly, the utility of spent mushroom substrate as a feed substrate for BSFL (or other insects) may depend on the mushroom type, the duration of fermentation, the inclusion of fruiting bodies, and the mushroom growth substrate itself (Li *et al.* 2021; Ventura *et al.,* 2023; Wei *et al.,* 2017).

The objective of the current study were thus to compare the performance and nutrient composition of BSFL reared on two underexplored waste streams from sustainable crop production (kernza straw and spent mushroom (*L. edodes*) substrate) and two widely available waste streams (spent coffee grounds and mixed institutional food waste), while replicating real-world environmental growing conditions. Results will improve our understanding of the feasibility of using BSFL to valorize these waste materials and provide solutions for both sustainable waste management and the growing demand for animal feed.

Materials and Methods

Experimental Diets

Four experimental diets were tested along with 100% chicken feed as the control diet: 1) 100% mixed food waste, 2) 80% chicken feed + 20% spent mushroom substrate, 3) 80% chicken feed + 20% spent coffee grounds and, 4) 80% chicken feed + 20% ground kernza straw. Feed substrate ratios for spent coffee grounds and spent mushroom substrate were based on previous work by Khaekratoke *et al.* (2022) and Li *et al.* (2021), respectively. No previous research has investigated kernza as a diet for BSFL. Thus, for comparability, we used the same ratio of 80:20 as the two other diets. The choice of using 100% mixed food waste in this study was to make for easy comparison with other studies.

The food waste diet was a mixture of food waste from the campus dining hall and consisted of leftover rice, bread, donuts, cake, meat, vegetables, and fruits, with a higher proportion of the carbohydrate sources. The leftover food waste was collected on December 15, 2023, and was gathered directly from the dining hall after meal service. Unwanted waste materials like straws, napkins, tins, and indigestible wastes like bones and hard seeds were separated by hand from the food waste materials. To ensure homogeneity, the food waste was ground with a Hobart 4822 meat grinder into a uniform paste.

Partially dried spent coffee grounds were collected from a campus café on December 15, 2023, and stored in a closed compost bin at -20°C.

Spent shitake mushroom substrate (*L. edodes*) was sourced from Vitruvian Farms, Wisconsin, USA, on December 15, 2023. Mushroom was cultured on 70% Red oak sawdust and 30% wheat hydrated to 60% moisture content for 11 weeks and harvested twice at a temperature range of 16-18 °C and relative humidity of 80-90%. The spent mushroom substrate was collected partially moist and ground by scrubbing with hand over a ¼ inch mesh sifting pan.

Second-year post-harvest dry kernza straw was sourced from Arlington Agricultural Research Station, ground using a Christy 8" lab mill mechanical grinder with a 1mm size mesh screen on November 22, 2023, and stored in a plastic bag at room temperature until use.

Organic Poultry Starter feed (Cashton Farm Supply, LTD., Cashton, Wisconsin, USA) was purchased from a pet supply store in Madison, Wisconsin, USA and stored at room temperature until use. The feed contained corn, peas, wheat, fish meal, crab meal, and special probiotix premix.

With the exception of kernza straw and chicken feed, all feed substrates were stored in a refrigerator at - 20 °C. Two days before the experiment, the feed substrates (food waste, coffee grounds, mushroom substrate) were transferred to a Binder UF V 700 Ultra-Low Temperature Freezer and allowed to reach -57°C before they were freeze-dried using a VirTis AdVantage Plus Model XL-70 freeze dryer. 240 g of experimental diet per container was measured and moisture (70% of the diet: 168 mL) was added to the diet and mixed by hand.

Experimental Design

This experiment took place at the University of Wisconsin-Madison Poultry Research Lab in January 2024. Larvae were put in stasis at five-day old by seller (PopWorms! TM Inc., Tifton, GA, USA)prior to shipping on January 9, arriving on January 13. Upon arrival, the larvae were stored in the plastic container they arrived in the supplier's substrate at an average temperature of 23 ºC and average relative humidity of 55% before the experiment began the next day (January 14th). For each diet, approximately 400 five-day-old larvae were hand counted and weighed collectively using an AG285 Mettler Toledo weighing balance. The larvae were then placed in the center of a plastic Rubbermaid container (13 cm wide x 13 cm long x 7 cm tall) on the rearing substrate (2.4 larvae/cm^2). Three containers per experimental diet were used, for a total of 15 containers. The feed volume was calculated for 12 days at a feed rate of 50 mg/larva/day, following Diener *et al.* (2009). 240 g of feed were added to each container at the beginning of the experiment to reduce the impact of handling, following recommendations by Bosch *et al.* (2020). Each container was covered with mesh netting (160 µm mesh aperture) held by a rubber band to prevent escape or contamination from other insects.

The larval containers were placed on three shelves of a wire shelving unit (91 x 61 x 137 cm). To ensure uniform rearing conditions across all treatments, the larval boxes were randomly redistributed across the three shelves every four days. The larvae were reared in the lab at ambient temperature. We used a smart thermos-hygrometer (H5075, Govee) positioned on the shelving unit, away from sunlight or air vents to closely approximate the larvae's conditions. Temperature and relative humidity were recorded three times daily at 800h, 1200h, and 1700h. An ambient temperature of 21.0 ± 2.0 °C (mean ± SD; range = 13.0 - 22.2 °C) and relative humidity of 15.0 ± 7.8 % (7.3 - 28.8 %) were recorded. Lights remained on 24/7, as chicks were also being raised in the room. On days 4 and 8 of the experiment, 60 and 15 mL of water were added to each container, respectively. The larvae were reared for 12 days following Bosch *et al.* (2020).

Larvae were weighed on day 0 (initiation of experiment), 4, 8, and 12 of the experiment. Larval weights on day 4, 8, and 12 were determined by randomly weighing three replications of 30 larvae at different locations in the container. Each of the sample were collected across the edges, center, bottom, and surface of the container. Subsequently, the sampled larvae were individually cleaned with paper towels and weighed before being reintroduced into their containers.

Harvesting and Processing

At the conclusion of the experiment on day 12, larvae were separated from the feed residue using forceps. Live larvae (no prepupae) were separated from dead ones, cleaned with a paper towel, counted to determine mortality, and weighed with an AG285 Mettler Toledo weighing balance. Live larvae exhibit movement and responsiveness to external stimuli, such as probing gently with forceps. On the other hand, dead larvae often appear motionless, dried, and discolored, while prepupae are dark brown in color and appear larger than larvae. After separation, the weight of the larvae per container was measured using an AG285 Mettler Toledo weighing electronic balance. Larvae from the same container were then placed in a 50 ml centrifuge tube, labeled with a permanent marker, and stored at -18 °C for >24h for proximate analysis. The residue (including frass) from each container was collected and the weight determined using an Ohaus SPE401 Scout® Pro electronic balance. Parameters related to growth performance and bioconversion efficiency were calculated on a fresh matter basis, using the following formulae:

i. Growth rate =

$$\frac{\text{average final body weight per larvae (g)} - \text{average initial body weight per larvae (g)}}{\text{days of trial}}$$

ii. $\text{Mortality} = \frac{\text{initial number of larvae} - (\text{final number of larvae})}{1} \times \frac{\text{initial number of larvae}}{100}$

iii. $\text{Waste reduction index (WRI)} = \frac{\frac{(\text{W}-\text{R})}{\text{W}}}{\text{D}} * \frac{100}{1}$

Where, W = total mass of rearing substrate distributed during trial (g); r = residue substrate; d = days of trial

iv. $\text{Feed conversion rate (FCR)} = \frac{\text{total feed added}}{\text{total final larval biomass}}$

Laboratory Analyses

Proximate nutritional and mineral analyses of the feed substrate and larvae were conducted by an external laboratory (Dairylands Lab, Arcadia, Wisconsin, USA). After the diet was prepared, feed samples were immediately collected into centrifuge tubes and labeled with a permanent marker for storage and analysis. The remaining feed substrates were then distributed into individual containers. Proximate analysis of the larvae was conducted one month after harvest. These analyses consisted of analytical determinations of moisture, dry matter, crude protein, fat (EE), crude fiber, calcium, phosphorous, and sodium. Crude protein and fat were determined using methods described by Association of Official Analytical Chemists (1999; methods 990.03 and 920.39, respectively), while crude fiber was determined using methods described by Association of Official Analytical Chemists (1979; methods 978.10). Mineral compositions were analyzed according to methods described by Association of Official

Analytical Chemists (2011; methods 14) and Association of Official Analytical Chemists (2017, methods 02). Crude protein and fat analyses were not conducted for one container of larvae fed the coffee ground-supplemented diet due to insufficient amounts of larvae.

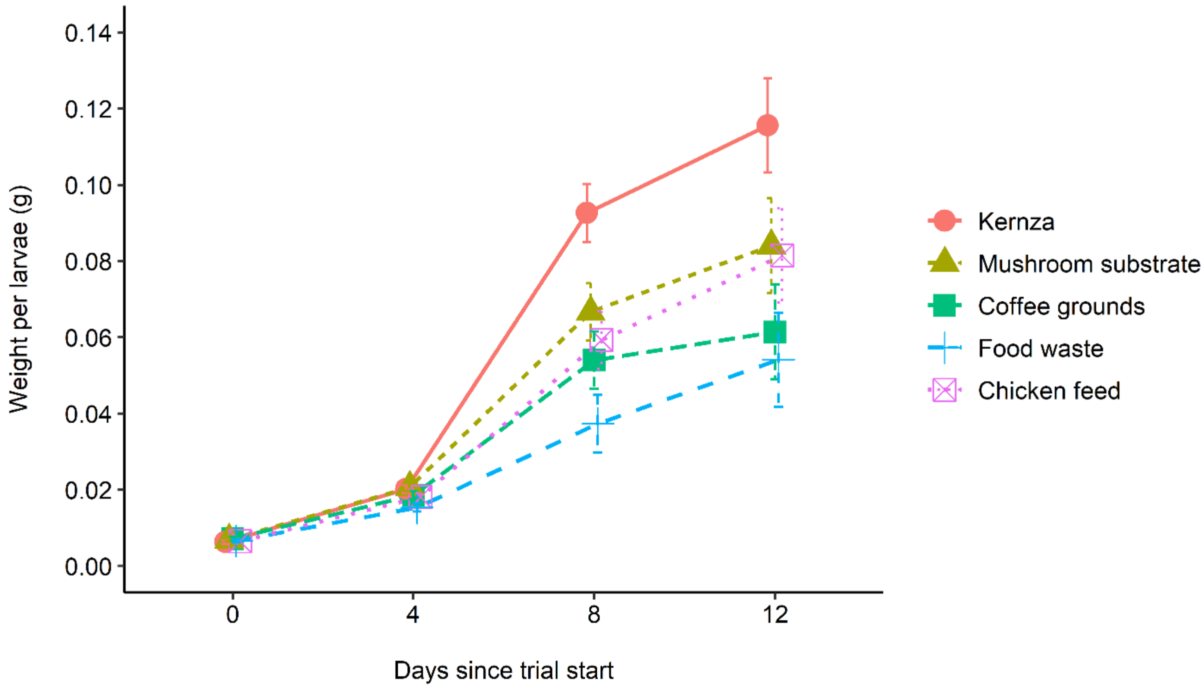
Data analysis

Descriptive and statistical analyses were performed using R, version 2023.9.1.494 (Team, 2023). For all models, residuals versus fits plots and Q-Q plots were visually inspected to confirm homogeneous variance and normality of residuals, respectively. The response variables (larval weight, growth rate, feed conversion ratio, waste reduction index) were fitted with the lm function in the stats package in base R (R 4.3.2) (Pinheiro *et al.,* 2021). Subsequently, we performed a one-way ANOVA followed by pairwise contrasts using Tukey's method with the emmeans package to examine the significant differences between treatments.

Results

The effect of the different substrates on larval growth over time is shown in Figure 1. Initial larval weights taken on Day 0 did not differ by diet ($F_{4,10} = 0.65$, $P = 0.638$). At the experiment initiation (day 0), the average larval weight was 0.007 ± 0.0004 g across all the treatment groups. Significant effect of the feed substrate on larval weight were observed on day 4 ($F_{4,10} = 4.09$, $P = 0.032$), day 8 ($F_{4,10} = 7.14$, $P = 0.006$) and day 12 ($F_{4,10} = 3.73$, $P = 0.041$) of the experiment. A higher average larval weight was found in larvae fed kernza-supplemented diets compared to those fed food waste on day 4 (KZ: 0.020 g; FW: 0.02 g), day 8 (KZ: 0.09 g; FW: 0.04 g) and day 12 (KZ: 0.12 g; FW: 0.05 g). Though not statistically different, larvae fed chicken feed had the second highest average larval weight (0.08 g) followed by larvae fed coffee ground-supplemented diets (0.06 g), and larvae fed mushroom-supplemented diets (0.08 g) on day 12.

Figure 1: Growth performance of BSFL over time. Mean larval weight indicated for day 0, 4, 8, and 12 (wet weight) on experimental feeds: 100% chicken feed (control), 100% food waste, 80% chicken feed + 20% spent mushroom substrate, 80% chicken feed + 20% coffee ground, and 80% chicken feed + 20% kernza straw.



There was significant difference in growth rate across treatments (Table 1). Larvae fed kernza-supplemented diets had the highest growth rate (9.11 mg/day) and showed significant difference compared to larvae fed food waste (3.96 mg/day). No other significant differences in growth rate between treatments were observed.

There was no significant difference in the effects of treatments on larval mortality. Larvae fed food waste had the highest larval mortality rate (15.6 %), followed by kernza-supplemented larvae (13.7 %), chicken feed fed larvae (12.4 %), and spent mushroom substrate-supplemented larvae (12.0 %), while larvae fed coffee ground-supplemented diets had the lowest mortality rate (5.7 %).

There was a significant effect of treatment on efficiency of feed conversion of the larvae (Table 1). Larvae fed food waste had the highest FCR (14.18) and was significantly different ($p < 0.05$) from larvae fed kernza-supplemented diets which had the lowest FCR (6.13). In other words, more than twice as much substrate would be required to produce 1 kg of BSFL when using food waste compared to the kernza-supplemented diet.

There was a significant difference in the impact of feed treatments on the ability of larvae to reduce waste. Larvae fed food waste diet and spent mushroom-supplemented diet had a significantly higher WRI of 6.09 ± 0.13 and 5.75 ± 0.13, respectively compared to larvae fed other diets. Larvae fed chicken feed had the lowest waste reduction ability (4.69 ± 0.13).

Table 1: Performance of BSFL fed 100% chicken feed, 100% Food waste, 80% Chicken feed + 20% spent mushroom substrate, 80% Chicken feed + 20% coffee ground, and 80% Chicken feed + 20% kernza straw (mean ± standard error)[1].

	CF	FW	MS	CG	KZ	F-Value	p-Value
Growth rate (mg/day)[1]	6.25±1.03^{ab}	3.96±1.03^{a}	6.43±1.03^{ab}	4.53±1.03^{ab}	9.11±1.03^{b}	3.80	0.040
Mortality (%)	12±7.08^{a}	16±7.08^{a}	12±7.08^{a}	6±7.08^{a}	14±7.08^{a}	0.28	0.890
Feed conversion ratios (FCR)[1]	8.57±1.32^{ab}	14.18±1.32^{a}	8.86±1.32^{ab}	10.75±1.32^{ab}	6.13±1.32^{b}	5.12	0.020
Waste reduction index (WRI)[1]	4.69±0.13^{a}	6.09±0.13^{b}	5.03±0.13^{a}	4.81±0.13^{a}	5.75±0.13^{b}	20.80	<0.001

[1] Result based on wet matter.

[2]Different superscript letters indicate significant differences ($p \leq 0.05$) based on one-way ANOVA with Tukey's HSD post-hoc test.

Proximate and mineral analyses composition of the initial feed substrates is presented in Table 2. Descriptively, food waste had the highest crude protein (CP) and fat content and lowest dry matter, and fiber content compared to the other diets. Sodium was highest and calcium and phosphorus were lowest in the food waste diet.

Table 2: Proximate and mineral analysis composition of feed substrates: 100% Chicken feed, Food waste, 80% Chicken feed + 20% spent mushroom substrate, 80% Chicken feed + 20% coffee ground, and 80% Chicken feed + 20% kernza straw[1]

Parameter	CF	FW	MS[1]	CG[1]	KZ[1]
Moisture (%)	45.9	65.3	50.4	49.5	45.3
Dry matter (%)	54.1	34.7	49.6	50.49	54.7
Crude protein (%)	18.3	22.3	18.7	17.85	15.3
Crude fiber (%)	5.8	2.5	8.4	7.39	10.3
Fat (EE) (%)	4.6	11.9	4.5	5.89	4.0
Calcium (%)	4.7	0.2	3.5	5.39	4.7
Phosphorus (%)	0.7	0.3	0.7	0.61	0.5
Sodium (%)	0.2	0.5	0.2	0.2	0.2

[1] Proximate analysis were conducted on the mixed diets.

Table 3 compiles the proximate and mineral content of the final larvae. The dry matter content of larvae fed food waste was significantly higher compared to larvae fed supplemented diets. The crude protein content was significantly lower in larvae fed food waste compared to larvae in all other treatments. Larvae fed kernza-supplemented feed had a crude fiber content that was significantly higher than other feed treatments (Table 3). Larvae in the food waste group had the highest fat content (33.5%) and were significantly different from those in the other groups. Larvae fed food waste had lower calcium (0.6%) and phosphorus (0.9%) content than larvae from all other treatments (Table 3). Larvae fed the mushroom supplemented diet had higher calcium content than larvae fed coffee grounds. Sodium content (0.2%) did not differ significantly between treatments.

Table 3: Proximate and mineral analysis composition of BSFL fed 100% Chicken feed, Food waste, 80% Chicken feed + 20% spent mushroom substrate, 80% Chicken feed + 20% coffee ground, and 80% Chicken feed + 20% kernza straw (mean ± standard error)[1]

Parameter	CF	FW	MS	CG	KZ	F-Value	p-Value
Dry matter (%)	31.8±0.58[a]	36.6±0.58[b]	32.4±0.58[a]	29.8±0.58[a]	30.9±0.58[a]	20.13	<0.001
Crude protein (%)	52.5±0.96[a]	46.4±0.96[b]	50.9±0.96[a]	52.4±1.17[a]	52.3±0.96[a]	7.26	0.007
Crude fiber (%)	6.1±0.17[a]	5.2±0.17[b]	6.7±0.17[a]	6.3±0.17[a]	8.0±0.17[c]	37.33	<0.001
Fat (EE) (%)	23.4±0.71[a]	33.5±0.71[b]	21.1±0.71[a]	21.4±0.87[a]	22.9±0.71[a]	50.68	<0.001
Calcium (%)	1.8±0.08[ac]	0.6±0.08[b]	2.0±0.08[c]	1.6±0.08[a]	1.8±0.08[ac]	49.21	<0.001
Phosphorus (%)	1.4±0.09[a]	0.9±0.09[b]	1.5±0.09[a]	1.4±0.09[a]	1.3±0.09[a]	7.35	0.005
Sodium (%)	0.1±0.02[a]	0.2±0.02[a]	0.1±0.02[a]	0.1±0.02[a]	0.1±0.02[a]	0.76	0.580

[1] Result based on wet weight.

[2] Different superscript letters indicate significant difference ($p \leq 0.05$) based on one-way ANOVA with Tukey's HSD post-hoc test.

Discussion

Hermetia illucens play an important role in the ecosystem, helping to transform waste materials that would otherwise go to landfills into nutrient-rich resources. This study was conducted to investigate the feasibility of rearing BSFL on different waste materials. The tested wastes materials were – kernza straw, spent mushroom substrate, food waste, and spent coffee grounds. The result of this present study will provide insights into novel ways of valorizing low-quality waste materials for improved larval performance.

It is well-known that the quality of the rearing substrate significantly affects the performance of BSFL. In this study, larvae fed food waste had a significantly lower final larval weight (Figure 1), growth rate, and feed conversion ratio compared to those fed kernza-supplemented diets (Table 1). A possible explanation for this could be attributed to the composition of the different waste substrates. It has been reported that larval performance are influenced by protein content of a diet (Oonincx *et al.* 2015). Interestingly, the CP content of food waste substrate in this study was higher compared to the kernza-supplemented diet, but this did not translate to higher larval weight or growth rate. It is probable that the low final weight of larvae fed food waste in this study was as a result of protein in the feed being consumed by the larvae but not efficiently assimilated. The high feed conversion ratio (FCR) value observed in larvae fed food waste diet in this study supports this assertion. In addition to the prebiotic fibers found in kernza straw which improves digestion and assimilation in BSFL (Gold *et al.,* 2018), the significantly higher final weight observed in larvae fed kernza-supplemented diets in comparison to larvae fed food waste in this study could be a result of the diet supplementation with high-quality reference feed material (chicken feed) which improved assimilation of these nutrients for larval development.

In the present study, food waste and kernza-supplemented diets had a significantly higher WRI compared to the other diets, indicating that the larvae were more effective at breaking down and reducing the mass of food waste and kernza-supplemented diets compared to other diets. Higher WRI values indicate a greater ability to reduce waste. The high fiber content of kernza straw in this study (Table 2) might have contributed to the high WRI by stimulating the growth of beneficial gut microbes which can improve digestion and nutrient assimilation (Boaru *et al.,* 2018). As a result, larvae were able to consume and breakdown these materials more efficiently, leading to higher waste reduction. This assertion is similar to findings by Gold *et al.* (2018) that larval gut microbiota can break down fibers into simple molecules and make nutrients available for larval development and growth. Additionally, kernza straw used in this study was ground into finer particles compared to other feed substrates, which may have made it easier for larvae to break down. Dortmans *et al.* (2017) in their study recommended shredding or grinding BSFL feed substrates to help improve the consistency of the nutrient available in the substrate to aid digestion in the larvae. The higher WRI observed in food waste may be due to the moisture content (65.3%) of food waste compared to moisture content of other feed substrates (coffee ground-supplemented diets, mushroom supplemented-diets, and chicken feed) with moisture content ranging from 45.88-50.43%. Previous research has reported that moisture content of BSFL diet is an important factor that affects production and waste reduction ability of the larvae (Bekker *et al.,* 2021). When the moisture content of BSFL feed is ideal, larval performance improves. For example, Fatchurochim *et al.* (1989) reported ideal moisture content for optimal performance and development of BSFL to between 40 and 70%. Water evaporation from substrate can lead to a reduction in the moisture content, which might artificially distort WRI by reducing the mass of the substrate without corresponding increase in the larval weight or waste reduction (Tokwaro *et al.,* 2023). In this study, food waste substrate had the highest moisture content (65.3%). It is possible that the significantly higher WRI of larvae fed food waste recorded in this study is as a result of water evaporation from food waste substrate, leading to lower food waste substrate residue. Previous study by Tokwaro *et al.* (2023) reported that evaporation losses contributed to the reduction of fecal sludge by BSFL. We recommend regularly monitoring and adjusting substrate moisture levels to control water evaporation from substrate and for a more accurate assessment of larval waste reduction ability.

Environmental conditions play an important role in the performance of BSFL, with sub-optimal conditions leading to less-than-optimal performance. The final weight of larvae fed chicken feed recorded in this study was lower than those reported by Miranda *et al.* (2019) and Miranda *et al.* (2020) for larvae fed Gainesville diet but comparable to those reported by (Broeckx *et al.* (2021) for larvae fed Gainesville diet. Additionally, the mortality rate recorded of larvae fed chicken feed in this study was similar to those reported by Jones and Tomberlin (2019) for larvae fed Gainesville diet but higher than those reported by (Broeckx *et al.* (2021) for larvae fed chicken feed. Compared to this study, Fitrina *et al.* (2021) reported lower FCR values than this study for larvae fed animal feed. Similarly, Diener *et al.* (2009) reported lower WRI for larvae fed chicken feed at feeding rate of 50 mg than this study. The mortality rate reported in this current study is higher than those reported by Broeckx *et al.* (2021) for larvae fed chicken feed. This variation in results between studies could be attributed to the suboptimal environmental conditions in this study. While previous studies used optimal temperature and relative humidity, this study attempted to mimic real-world rearing conditions of BSFL, which may have had an impact on the overall larval performance like mortality, for example. In their study examining how temperature affects the development of BSF, Tomberlin *et al.* (2009)

reported that temperature between 27 and 30 °C led to higher survival rate, while Silva *et al.* (2020) reported that low relative humidity decreased the survival rate of larvae in their study. Thus, if optimum environmental conditions reported in other studies were replicated, it is possible that larvae could have performed better. Another reason for the variation in results between studies could be attributed to the different feeding regimes frequency used by these studies. For example, this present study introduced feed substrate at once at the beginning of the experiment, while studies by Diener *et al.* (2009) and Broeckx *et al.* (2021) fed the larvae at different intervals throughout the experiment. Previous studies have established that feeding frequency has a great impact on the performance of BSFL (Banks *et al.,* 2014; Parra Paz *et al.,* 2015)

The nutritional composition of feed substrates can largely influence the nutritional composition of larvae. In the present study, larvae fed food waste had a significantly higher DM and fat content, but lower CP, CF, Ca, and P content compared to larvae fed other feed substrates. Initial proximate analysis of the feed substrates showed that food waste had the numerically lowest DM and highest fat and CP content (Table 2). Generally, BSFL are highly efficient in breaking down and assimilating nutrients from their feed. When they are fed feed high in fat content, they effectively metabolize and store these fats in their bodies, leading to an increase in their body fat content. Our findings agree with previous study by Franco *et. al.* (2021) that the nutrient content of larvae is dependent on the substrate. On the other hand, the CP, Ca, and P were lower in larvae fed food waste compared to other feed substrates. It is possible that supplementing these low-quality feed materials with high-quality diets improved their nutritional composition. The significantly higher CP, Ca, and P in larvae fed supplemented diets in this study supports this assertion. The CP content of larvae fed supplemented diets in this study

(Table 3) is higher than those reported by previous studies for larvae fed chicken feed, animal feed, and chicken feed, respectively (Adebayo *et al.,* 2021; Diener *et al.,* 2009; Lalander *et al.,* 2019). Low fat content were reported on the supplemented substrates used in this study. Studies by Finke (2013) and Meneguz *et al.* (2018) have also reported low fat contents in BSFL with high CP contents for larvae fed fruits and vegetable waste. The fat content of larvae fed chicken feed in this study (Table 3) was lower compared to those reported by Tschirner and Simon (2015) and Eggink *et al.* (2022) for larvae fed mixture of middling (broken pellets, spilled grains, grinding dust) and chicken feed, respectively. Furthermore, the fat content of larvae obtained in this study were higher than those reported by Pamintuan *et al.* (2020) for larvae fed rice straw but similar to those reported by other studies for larvae fed fruit and vegetable wastes, Gainesville diet and commercial tilapia feed (Fischer and Romano, 2021; Hadj Saadoun *et al.,* 2020; Perez-Pacheco *et al.,* 2022). These differences in results can be attributed to the difference in the nutritional composition of the different feed substrates (Franco et. al. 2021) and stage of development of the BSF, i.e., larvae versus prepupae (Liu *et al.,* 2017).

The results from this study indicated that feed substrates influenced the fiber content of the larvae. The initial chemical composition analysis of the feed substrates showed that kernza diets had the highest fiber content among all tested substrates. Correspondingly, larvae fed kernza-supplemented diets had significantly higher fiber content than all other treatments. The high fiber content in kernza can be particularly beneficial, as fibers are known to help stimulate the growth of beneficial gut microbes, thereby enhancing digestion and assimilation (Gold *et al.,* 2018). This improved gut health and digestive efficiency is likely to improve the performance of larvae reared on kernza-supplemented diets, as observed in this study. It is possible that the presence of fiber in the diet may have aided the movement of larvae in the substrate by providing more anchor points for the larvae to move with and feed (Abbas *et al.,* 2024; Gianetti *et al.,* 2022). This may lead to an increase in larval weight and substrate reduction as larvae are able to move better and have access to substrate. This could also explain the high larval waste reduction index of larvae fed kernza-supplemented diets in this study. This finding is supported by previous studies that have shown increases in larval growth by 22% through gains in both protein and lipid by pure cellulose (Abbas *et al.,* 2024). The mortality rate of larvae fed kernza-supplemented diets in this study is lower than those reported in Manurung *et al.* (2016) for larvae fed rice straw at a daily feeding rate of 50 mg per larvae. However, larvae fed kernza-supplemented diets in this study had lower FCR and higher CP than those reported by Danielli *et al.* (2019) for larvae fed mixed high fiber diet and lower mean larval weight than those reported by (Gao *et al.,* 2019) for larvae fed fermented maize straw.

From the result from this study, larvae fed mushroom substrate and coffee ground supplemented diets had no significant difference in performance or nutrient content from larvae fed chicken feed, indicating that supplementing high-quality diets with waste substrates has the potential to improved larval performance. Previous study by (Khaekratoke *et al.,* 2022) reported a higher growth rate, larval weight, WRI and lower CP contents for larvae fed a mixture of fruit and vegetable reside supplemented with fermented spent coffee ground (80:20) compared to this study. Similarly, this study recorded lower mortality than those reported by Fischer *et al.* (2021) for larvae fed a mixture of spent coffee ground and donut dough (1:1). On the other hand, the larval weight recorded for larvae fed mushroom substrate-supplemented diets in this study were lower than those recorded by Li *et al.* (2021) for larvae fed a mixture of *L. edodes* mushroom substrate and food waste (20:80). In comparison to the current study, Soomro *et al.* (2024) reported lower mortality but comparable FCR for larvae fed a 80:20 mixture of soybean curd reside and mushroom root waste. In addition, Cai *et al.* (2019) reported lower WRI for larvae fed golden needle mushroom root waste (*Flammulina velutipes*) compared to this study.

BSFL can decompose a wide range of waste materials, including straw and several studies have been conducted to support this (Gao *et al.,* 2019; Manurung *et al.,* 2016). However, some studies have utilized several methods of pre-treating feed substrates to improve insect performance. For example, Zheng *et al.,* (2012**)** reported that fermenting rice straw with Rid-X microbe significantly enhanced the bioconversion efficiency of BSFL. In addition, Khaekratoke *et al.* (2022) reported that adding 20% fermented coffee ground to vegetable pulp resulted in the high WRI and low FCR values, while Isibika *et al.* (2019) found that pretreatment of banana peels by microbial fermentation or non-protein nitrogen resulted in higher final larval weight compared to untreated banana peels. It is therefore plausible that pre-treating waste materials used in this study would further improve the performance outcome of BSFL in this study. Therefore, future research should explore pretreating feed substrates to further enhance the performance of BSFL.

Feeding waste streams to BSF have emerged as a promising strategy for transforming waste materials into valuable biomass. Although altogether the result from this study suggests that kernza straw is a promising feed material for BSF when supplemented with a reference diet, utilizing it for such comes with a potential drawback. One key challenge is that kernza straw is also utilized as winter additive in rations for livestock, despite being of low quality (Hunter *et al.,* 2020). Given that kernza farming is still at its early stages and farmers grow the crop for both grain and straw (Lanker *et al.,*2020), one way to navigate this could be prioritizing the use of kernza straw as feed for BSFL, especially from kernza grown primarily for grains or sourced from farmers without livestock. This ensures the efficient use of the straw to produce high-quality feed resources for livestock. However, since kernza is grown not just because of its grain and forage, but also because of the soil health benefits it provides, it is recommended that not all the kernza straw be harvested as feed materials for BSF.

In this experiment, chicken feed was combined with waste streams at a supplementation ratio of 80:20. The choice of supplementing chicken feed with feed substrates in this study was because it is a high-quality feed and has defined nutrients. However, using a such supplemental ratio of high-quality rearing substrate, as observed in this study for large scale rearing of BSF may not be environmentally and economically viable and defeats the purpose of circular economy, which seeks to maximize the use of waste materials and produce useful products and reduce reliance on high-cost inputs (Bava *et al.,* 2019). Further research should be conducted to examine the effect of varying supplementation ratios of reference diets on larval performance.

Finally, this study tried to limit the use of energy and mimic real-world rearing of BSF. Thus, environmental conditions, including temperature and humidity were not controlled, while light was turned on all through the experiment because chicks were also being raised in the laboratory room we used. Another limitation of this study is the small sample size, which may not fully capture the challenges or opportunities associated with BSF production. Future studies should be conducted at industrial scale to assess the lifecycle impact of large-scale BSF production. Furthermore, to better understand the economic viability of using kernza as a feed substrate for BSFL, cost-benefit analysis should be conducted comparing the use of kernza as feed substrates for BSFL versus feeding them directly to livestock, while long-term studies should be conducted to examine the effect of varying supplementation ratios on larval growth, bioconversion, and nutrient composition.

Conclusion

The commercial and small-scale use of BSFL to manage waste and generate nutrient-rich larvae has been gaining attention across the globe, and BSFL systems could potentially reduce the cost of conventional animal feed. Larvae reared on diets supplemented with chicken feed had high CP contents, indicating that although the nutritional needs of BSFL is still unknown, supplementing lower quality waste streams with high-quality feed substrate (chicken feed) may be suitable for growing BSFL and generating protein. Results from this study demonstrate that BSFL can be reared on all tested substrates, including less explored crop residues and mushroom industry by-products. However, the short duration of the study necessitates future experiments evaluating the impact of these experimental feeds on the insects throughout their entire lifecycle and on their reproductive capacity.

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Chapter Three: Curriculum Evaluation Using Principles of Agroecology

Abstract

Curriculum evaluation is an important part of the educational process, yet its complex nature makes it challenging to undertake. This paper presents a framework for evaluating the Kernza® educational curriculum for high school education using the principles of agroecological education. The evaluation framework comprises five principles: experiential and holistic learning, transdisciplinary approach, awareness and communication, inclusion and diversity, and farmer-to-student/peer-to-peer learning. Using questionnaires, we assessed ‘what is a grain?’ lesson for the presence or absence of these principles. After developing this evaluation framework, there was a feedback process where we walked through the evaluation framework with the curriculum developers to review and implement feedback. This study underscores the importance of integrating agroecological education principles in developing sustainable education curricula that will equip future agricultural professionals with relevant knowledge and skills to address complex agricultural challenges.

Introduction

As the global population increases and climate change intensifies, the competition for resources like land, water, and fossil fuels becomes even more severe. To address these challenges, we need to design educational curricula in such a way that effectively prepares future professionals to both mitigate against and adapt to environmental change. The advent of the Green Revolution in the 1960s significantly boosted crop yields with the goal of reducing hunger, but also came with some unintended consequences such as soil degradation, reduction in soil fertility, water shortages, reduction in genetic variation, rural impoverishment among others. Thus, we need to train future professionals on how to become agents of change in our current agriculture and food systems. One of the ways we can train them to address these issues is by adopting a comprehensive teaching approach that takes the biophysical, economic, and social dimensions of food production into account to enable them to create sustainable and equitable food systems that are environmentally sound, economically viable, and socially just.

There has been a shift in how consumers, community, and society perceive agriculture and food in the last decade (Hassoun *et al.,* 2022; Krystallis *et al.,* 2012; Sesini *et al.,* 2012). This shift is gaining momentum as more people are increasingly becoming aware of the limits of fossil fuels, water, arable land, as well as negative effects of conventional agriculture on the environment and human health. This growing awareness is driving a movement towards more sustainable practices that protect the environment and human health. And so more than ever, it is now important to equip future generations with a multi-perspective approach to address these complex challenges in our agriculture and food systems.

The concept of agroecology is dynamic and has gained prominence over the years (IAASTD, 2009; IPES-Food, 2016). As its prominence spread, so did its definition by institutions and countries to reflect their peculiar situations. In any way, all of these definitions recognize that agroecology is transdisciplinary in nature and embraces science, a set of agricultural practices, and a social movement (Méndez *et al.,* 2013; Wezel *et al.,* 2009). As a science, Francis *et al.* (2003) defines agroecology as the "ecology of food systems, encompassing the social, ecological, and economic dimensions". As a social movement, "agroecology integrates ecological principles with social values while prioritizing sustainability, fairness, and community resilience" (Wezel *et al.,* 2020). As a set of agricultural practices, "agroecology aims to leverage natural processes, foster interaction amongst agroecosystem elements" (Gliessman, 1990), "reduce reliance on synthetic farm inputs, and integrating ecological principles and ecosystem services for the development of agriculture" (Wezel *et al.,* 2014)). These three articulations of agroecology (a science, set of agricultural practices, and social movement) are intertwined and together give a holistic view of agriculture (Gliessman, 2018, Agroecology Europe, 2017). As such, across agricultural, food, nutritional, and social sciences landscapes, agroecology has been described as transdisciplinary, participatory, and action-oriented (Méndez et. al. 2013).

Agroecological education stems from sustainable agriculture, infuses bits from different disciplines, and gives learners a holistic understanding of challenges. It requires the study of the relationship between agriculture, our environment, and society (David and Bell, 2018). However, this, in no way, implies that the learner has to be an expert in all the fields.

The current traditional system of agriculture education majors on the biological and economic returns dimension of crop production, and thus, educators working with future agriculture professionals are tasked with helping them adopt a multi-dimension approach when addressing agricultural problems. This is one of the goals of the Kernza® in context education project (The Land Institute, 2024).

Integrating experiential learning into educational curriculum enhances students' ability to observe, analyze, and solve real-world problems, and thus prepares them to solve future problems. The Kernza® in context educational curriculum is designed to tell the story of Kernza® and how it fits into our communities, farming systems, and the planet as a whole. The curriculum equips learners with tools they need to help solve real-word problems and create a more sustainable future. To make sure the curriculum is effective and meets intended goals, we aimed to develop a framework that can be used by teachers, parents, students, and stakeholders to evaluate the curriculum using the principles of agroecology. However, students often struggle with making direct observations through observation, interviews, or questionnaires, and taking concrete actions. This lack of hands-on experience hinders their creativity and ability to produce quality scientific works (Baidowi *et al.,* 2015). To address this, experiential learning models could be used to enhance students' creative and critical thinking skills in scientific reporting. Experiential learning involves engaging in learning activities over a period of time to take concrete actions (Sumarmi, 2015) and has different stages that include real experience, reflective observation, conceptualization, and implementation (Ives-Dewey, 2009; Kolb, 2014).

Experiential learning equips students to solve problems in diverse fields by thinking critically and emphasizes gaining experience by solving problems through hands-on activities with the help of a teacher (Baidowi *et al.,* 2015). Several studies have reported that experiential learning plays a significant role in improving the ability of students to think critically and creatively (Kurniawan *et al.,* 2019; Nurhasanah *et al.,* 2017). Therefore, to truly enhance the effectiveness of experiential learning within the Kernza® in context education curriculum, a thorough evaluation process is essential.

However, ensuring the effectiveness of any curriculum requires a thorough evaluation process to meet intended objectives and continuously improve to meet learners' needs. Thus, to ensure the success of a newly developed curriculum, it is important that a quality assurance mechanism is put in place. There have been different definitions of curriculum evaluation in the literature. Generally, curriculum evaluation can be seen as the systematic approach used to gather and analyze relevant information to evaluate how effective a curriculum is at achieving its educational objectives and facilitate enhancement (Nichols *et al.,* 2006).

As a multifaceted process in education, curriculum evaluation consists of complex different dimensions. It can be categorized based on what to evaluate – micro and macro; based on what stage the evaluation occurs – pre-use, in-use, and post-use; and based on its purpose – summative, which assesses the quality of a curriculum, and formative evaluation, which aims to shape and enhance the curriculum (Tellioğlu, 2016). For macro evaluation, the goal curriculum development is on general issues like the formatting of the modules, how they are related to each other, and how the objectives of the curriculum can be achieved (Tomlinson, 2003). Conversely, micro evaluation is more detailed, looking at the modules and single courses, how teaching is done exactly, the learning materials, and teaching materials used within a course or module (Ellis, 1997; McGrath, 2002). Pre-use evaluation is generally more difficult to successfully carry out because of lack of experience in applying the curriculum to evaluate, while the goal of in-use evaluation is to assess the decision behind the module selection in the pre-use stage. Evaluation at the in-use stage might help address what worked well, what was changed when the module was taught in the past, as well as gathering information on all the stages of teaching. For post-use evaluation, the goal is to evaluate curriculum that has already been established, based on experiences with its quality, effectiveness, and outcome (Cunningsworth, 1995; McGrath, 2002).

For curriculum development to be effective, there has to be a comprehensive, perhaps even more structured evaluation framework to ensure stability and adaptability of the lessons or programs. Tellioğlu (2016) describes two levels of framework for curriculum evaluation (FCE): definition and execution. The definition level of FCE offers a framework for assessing a curriculum as a fixed, overarching summary of multiple components of a study – aim and objectives, structure, assessment mechanisms, quality assurance, interim regulations. At the executive level, FCE views the curriculum as a changing and detailed entity involving resources, processes, and outcomes, which are determined based on various stakeholders involved. These stakeholders include students, teachers, school staff, and alumni, as well as industries. For this current study, the curriculum was evaluated at the micro level at both the pre-use and in-use stage with a goal to further enhance the quality of the curriculum.

When an evaluation framework is successful, its content can then be adapted to fit the changes that may occur both in the industry and the academy. In addition, evaluation can help develop a sense of ownership and its result can affect both the curriculum itself and the teaching environment and methods of teaching of the teachers (Nation and Macalister, 2010). Consequently, it is important that the results of the curriculum evaluation is published with context and the reason for judgement clearly spelt out and easy to understand for all stakeholders addressed. This can be done orally or with written reports. However, for a successful evaluation to take place, parameters that are relevant for the evaluation of knowledge, skills, and competence must be identified. This study attempts to use the principles of agroecological education to evaluate educational lessons developed for high school students by the Kernza® in Context educational curriculum.

As reported by Caldart (2003), the Movimento dos Trabalhadores Rurais Sem Terra (MST, Landless Rural Workers Movement) in Brazil, establishes five objectives for field education programs: promotion of food sovereignty, promotion of land reform, democratization of land use, establishment of new technology and power paradigm, and establishment of a productive logic based on cooperation. Similarly, the Via Campesina (LVC) Agroecology Institutes in Latin America" (IALA), established the following philosophical agroecological principles in education: education based on, and for, social transformation: the aim is to bring about social transformation, challenging existing power structures and promoting social justice within the food system; education based on, and for, diversity: recognize the importance of diverse perspectives and knowledge systems and value and promote the inclusion of different voices, experiences, and ways of knowing in the educational process; education based on, and for, work and cooperation: places emphasis on practical skills and hands-on learning and value the work and cooperation involved in sustainable agriculture and promote collective action and solidarity and; education based on, and for, rebellion: encourage critical thinking and questioning of the dominant agricultural paradigm and aims to empower individuals and communities to challenge oppressive systems and engage in transformative action. These principles are tied to logical bases and should be rooted in a dialogical relationship between action-reflection-action. This means that learning, more than being theoretical, is also practical, with a constant cycle of taking action, reflecting, and taking further action.

The above principles of agroecology focus on different approaches that aim to promote sustainable agriculture and food systems. Thus, we can adapt these principles of agroecological education for curriculum evaluation into:

i. Experiential and holistic learning: this encourages hands-on learning and approaches that takes into consideration how interconnected the biophysical, economic, and social aspects are, and places emphasis on observing, participating, taking action, engaging in dialogue, reflecting, and envisioning as key for developing skills (David and Bell, 2018; Francis *et al.,* 2011).

ii. Transdisciplinary approach: this promotes a transdisciplinary approach to education and integrates knowledge and expertise from diverse fields through seeing, learning, and discovery as a social process, as well as different types of knowledge system (local, experiential, indigenous, etc.), including adopting a problem-based focus to help learners solve problems in real-life situations (Belsky, 2002; Méndez *et al.,* 2013). In this approach, collaboration and comprehensive understanding of complex challenges and solutions related to sustainable agriculture is encouraged.

iii. Awareness and communication: agroecological education recognizes the importance of raising awareness among consumers and stakeholders in the food system (Altieri *et al.,* 2012; Palomo-Campesino *et al.,* 2018; Zeng *et al.,* 2023). The aim here is to highlight the benefits of agroecology, the advantages of choosing agroecological products, and how consumer choices can significantly impact agroecological production and contribute to building a more resilient food system.

iv. Inclusion and diversity: agroecological education recognizes the importance of including diverse groups – women, youths, people of color, LQBTQ+ – in sustainable agriculture, aims to create opportunities for them to be able to actively participate and build capacity, and takes into account their specific needs and perspectives (Alkon and Norgaard, 2009; Murray *et al.,* 2020).

v. Farmer-to-student/peer-to-peer learning education: agroecological education recognizes the need for farmer-to-student/peer-to-peer learning and popular education and values it as an effective method of promoting innovation among farmers and sustainable agricultural development (Goris *et al.,* 2021). By farmer-to-student, we mean agroecological education through on-farm learning experience between students, farmers, and nature and by peer-to-peer, we are referring to learning that takes place when learners interact with each other.

These principles align with the broader framework of agroecology which consist of 10 elements of agroecology developed by the FAO – diversity; synergies; efficiency; resilience; recycling; co-creation and sharing of knowledge (describing common characteristics of agroecological systems, foundational practices and innovation approaches); human and social values; culture and food traditions (context features); responsible governance; circular and solidarity economy (enabling environment). Thus, the objective of this study were to: (i) develop a framework for evaluating curriculum using principles of agroecology (ii) use feedback from the curriculum developers on the evaluation tool to improve the evaluation tool.

Research Setting and Methodology

This research aimed at developing a framework for evaluating lessons in the Kernza® in context educational curriculum of The Land Institute using the principle of agroecological education. The methodology section outlines the process of developing, evaluating, and refining this curriculum as described in Figure 2.

Development of the Evaluation Tool

To create an effective evaluation tool for the curriculum, we adapted the principles of agroecological education in the literature into a structured framework. These principles include experiential and holistic learning, transdisciplinary approach, awareness and communication, inclusion and diversity, and farmer-to-learner/learner-to-learner education. Each principle was translated into specific, measurable criteria to ensure that the lessons were evaluated in detail.

Evaluation Process

Using the adapted principles of agroecological education, we developed a questionnaire to evaluate each lesson of the Kernza® in context educational curriculum. The questionnaire (Table 4) included specific, detailed questions related to each principle to assess the presence and absence of each agroecological education principle in the lesson.

Questionnaire Design

The questionnaire consisted of questions aligned directly with each principle of agroecological education for each lesson. For instance, questions related to experiential and holistic learning assessed whether the lesson provided hands-on activities, encouraged understanding of interconnectedness, and incorporated active learning activities.

Lesson Evaluation

Using the questionnaire (Table 4), one of the lessons in the Kernza® in context curriculum was evaluated for the presence or absence, as well as depth of inclusion of these principles of agroecological education. The results were used to identify strengths and areas for improvement in the curriculum.

Feedback from Curriculum Developers

One of the objectives of this study was to gather feedback from the curriculum developers and use it to further refine the evaluation framework. This process is important for ensuring that the evaluation framework aligns with the needs and goals of the educators, is practical for implementation, and efficiently incorporates agroecological principles. The feedback process involved presenting and explaining the evaluation framework and sample of evaluated lesson to the developers, answering questions about the agroecological education principles and evaluated lessons, and discussing potential improvements, and analyzing and integrating feedback. This process, in itself, is an example of agroecological education in action because it involved collaboration and participatory approach, making sure that inputs from those directly involved in the implementation of the curriculum is integrated in the evaluation process.

Figure 2: Process of curriculum evaluation

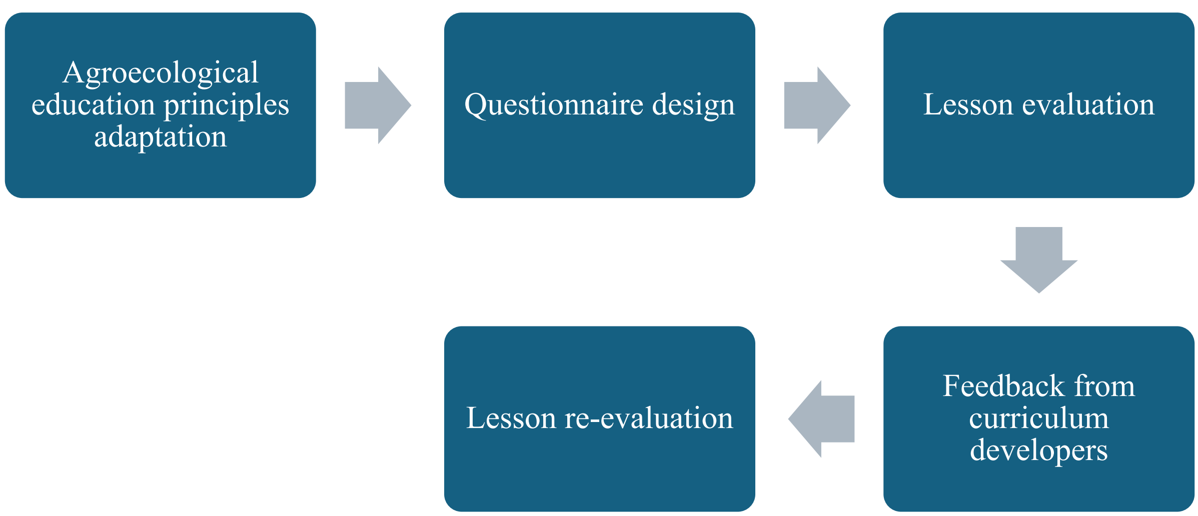

Table 4: Questionnaire containing the principles of agroecological education used to evaluate the lesson.

	Principles of agroecological education	Question
1	Experiential and Holistic Learning: This involves assessing if the lesson engages the learner in hands-on activities and offers a holistic perspective on agroecology.	Did the lesson provide opportunities for practical application of theories and concepts?
		Did the lesson encourage the understanding of interconnectedness between environmental, economic, and social aspects of perennial grain farming?
		Does the lesson incorporate active, experiential learning activities? For instance, does it encourage students to research and observe Kernza® and its environmental benefits?
2	Transdisciplinary Approach: This principle deals with how the lesson integrates knowledge from diverse	Were multiple fields of knowledge and expertise integrated into the lesson?

	fields, fostering a comprehensive understanding of the complexities of sustainable agriculture.	
3	Awareness and Communication: This principle assesses if the lesson educates students about the advantages of agroecology and the impact of their consumer choices on the environment.	Did the lesson raise awareness among potential consumers and stakeholders about the benefits of agroecological farming?
		Did the lesson communicate the importance of choosing agroecological/sustainable products and how their choices can impact on the food system?
4	Diversity and Inclusion: This principle is about ensuring that the lesson promotes the participation of women and youth in sustainable agriculture.	Were opportunities created for the participation of women and youth or other disadvantaged groups in the lesson, or did the lesson highlight the role of these groups in sustainable agriculture?

5	Farmer-to-student/peer-to-peer Learning Education: This principle involves evaluating if the lesson promotes farmer-to-student or peer-to-peer learning among students.	Did the lesson include the experiences, perspectives, and knowledge of farmers or players in the food system?
		Does the lesson provide opportunities for learners to engage with farmers practicing sustainable farming techniques or peers?

For each principle of agroecological education used in this evaluation, an assessment was made based on the presence or absence of any of the principles. The results were then used to further refine and improve the lesson to align them closely with the principles of agroecological education.

Using our adapted principles of agroecological education, we evaluated the lesson, "what is a grain?"

Lesson: What is a grain?

Main Idea of the lesson: The main idea of this lesson is that grains are important to many diets and cultures across the globe because they provide essential nutrients. As a result of their widespread presence in both landscapes and diets, there is a significant opportunity to transform our global food system from one that is extractive to one that is regenerative.

Driving Question of the Lesson: What is the importance of grains in human diets? What effect do grain crops have on human livelihood and ecological well-being?

Lesson Outcomes: It is expected that at the end of the lesson, students will be able to:

i. List all four major grain types (Cereals, Pseudocereals, Oilseeds, Legumes).

ii. Describe the grains that are part of their daily diets.

iii. Name the significant nutrient categories that grains provide.

iv. Explain why access to diverse types of grains is important for nutritious diets and healthy landscapes

This lesson was then divided into two sections: the lesson component and lesson outline. In the lesson component, student had access to a 24-hour food log, food calorie calculator, and a short read on "what the world eats". In the lesson outline section, students were asked to create a list of food categories that contained grains and asked to stand up every time a teacher reads out a category containing food they have eaten in the past 24 hours. As part of the post lesson assessment, students were asked to fill out their 24-hour food log and, using the food calorie calculator, look up the caloric values of what they have filled in their food logbook and answer reflection questions based on their answers. As a closing activity, students are asked to share one of their reflection questions with the class.

Results and Discussion

The "what is a grain?" lesson incorporated some agroecological elements but could also improve on some of its aspects. Below, we describe our evaluation of this lesson, highlight what agroecological element was or was not incorporated in the lesson, their depth of inclusion and impact on learners' understanding, and make recommendations for how the lesson can be improved to include these agroecological education principles.

Principle 1: Experiential and Holistic Learning

The lesson had the student perform hands-on activities like filling out the 24-hour food log and using the food calorie calculator to check the value of what they have eaten in the past 24 hours. This is an important aspect of agroecological education because through these students will be able to gain some skills and deeper understanding of grains by engaging in these activities. Although part of the driving question of this lesson is what effect grain crops have on human livelihood and ecological well-being, there was no activity in the lesson to answer this question. Furthermore, the lesson did not fully address the interconnectedness of the environmental, economic, and social aspects of grain farming. The limited scope of experiential learning activities may limit the ability of students to fully understand the broader implication of grain farming on the livelihood and ecological well-being of humans. Thus, this lesson could integrate activities or discussions that connects how grain production affects the environment, communities, and the economy. As an example, the lesson could discuss how grain farming affects soil health, water quality, local and global economies, and communities. For example, students can collect water samples from nearby streams or rivers and test for the presence of contaminants such as nitrates and phosphates, which are often linked to agricultural runoff. They can collect, test and compare water samples from rivers or streams near grain farms to those from less agriculturally intensive areas.

Principle 2: Transdisciplinary Approach

The lesson touches on nutrition and food system but does not integrate knowledge from different fields like social science and economics, for example, to include a problem-based lesson approach, thereby missing an opportunity to provide a holistic and deeper understanding of the intricacies of grain and grain production. As such, students would learn but miss out on learning from a multi-disciplinary approach and may not be able to solve real-life problems that involve applying multifaceted solutions. Consequently, to improve this lesson, students could be engaged with case studies where, for example, students could be tasked with analyzing how the availability of different type of grains impacts both nutrition and economic well-being of people in different regions of the world, then discuss potential solutions to improve access in underserved areas.

Principle 3: Awareness and Communication

This lesson raises awareness on the importance of grains in diets but fails to emphasize the broader impact of consumer choices of these grains on our environment and food systems. The implication of this is that learners may be left unaware of the important role they can play in promoting sustainable (grain) farming. The lesson could be improved by including a discussion on how consumer choices affects agricultural production and contribute to sustainable agriculture. For example, students could be asked to draw some parallels between different grains: kernza, wheat, corn, and so on.

Principle 4: Inclusion and Diversity

The lesson does not talk about inclusion and diversity and makes no mention of any diverse group. This could lead to a lack of awareness about the contribution of different groups to grain production. To improve this lesson in this section, students could be asked to discuss how grains are used by different cultures and if they have experiences about how grains are used by different cultures, why it is important preserve indigenous grain varieties, and grain production around the world.

Principle 5: Farmer-to-Student/Peer-to-Peer Learning and Popular Education

The lesson had no element of farmer-to-student learning or peer-to-peer engagement. This can limit students' practical understanding and appreciation of grain production and reduce their ability to share knowledge among themselves. To incorporate this aspect, the curriculum developers could include a field trip or virtual visit from a local farmer (or any player in the food system) to share their knowledge and experiences with grain production. Another way to incorporate this aspect is to have students read or watch an interview of a local farmer answering questions about their experience with growing grains. To incorporate peer-to-peer education, the lesson could include group discussions or peer-led presentations where students share their own research on different grain types and their impacts on the agri-food system, followed by collaborative projects where they are tasked to work together to develop strategies for sustainable grain production.

The evaluation of the "what is a grain?" lesson gives an understanding of its effectiveness (in terms of presence or absence and depth of inclusion of agroecological principles) and what aspects of the lesson needs to be improved. Although the lesson incorporated some aspects of experiential and holistic learning and included knowledge from nutrition and food system, these aspects could be improved upon. For example, to incorporate elements of experiential learning and transdisciplinary approach, students could be asked to research on the environmental impacts (soil health, water usage, carbon footprint) of conventional grain production versus kernza grain production, discuss on how their choices could support more sustainable farming, and present their findings in class. In addition, prior to class, they could be asked to read articles or documentaries that highlight the importance of crop (grain diversity) for a more resilient food system. Furthermore, the lesson did not include elements of inclusion and diversity or farmer-to-student learning or peer-to-peer learning. This could be improved upon by having students research on traditional grain crops grown across different parts of the world, how they are grown, their cultural significance, and nutritional benefits. This can help facilitate the exchange of knowledge among and between students, allowing them to learn from each other's research. Field trips or virtual tours to farms, processing facilities, and retail stores could also be organized so that students can see firsthand how these crops are grown, processed, and/or packaged.

After this tool was developed and tested, we had meetings with the curriculum developers from The Land Institute to gather feedback. The discussions centered on how best to integrate agroecological education principles and effectively use the tool within their curricula. We collaboratively worked through a lesson and addressed questions along the way.

One significant piece of feedback we received from the curriculum developers was the suggestion to evaluate the integration of agroecological principles at the module level, rather than at the individual lesson level. The rationale was that, in a high school setting, where class periods typically range from 60 to 90 minutes, it may be unrealistic to incorporate every principle into a single lesson. Although this evaluation approach offers practicality, we identified potential drawbacks, such as losing sight of both the overarching goals and finer details that can emerge when evaluating lessons in isolation. Additionally, we considered the concern that teachers across different schools often select individual lessons that align with their specific teaching needs, rather than using entire modules. This variability in lesson selection makes it important for evaluations to provide meaningful insights at both the lesson and module levels.

Another valuable suggestion was the inclusion of a bar graph overview to visually represent the integration of different agroecological principles within each lesson. One curriculum developer, Lydia, highlighted that this visual tool would provide a quick reference for teachers, helping them see which principles are emphasized in each lesson. For instance, if a lesson scores high in experiential learning and/or awareness and communication but low in farmer-to-learner or learner-to-learner education, this would be clearly reflected in the bar graph. This addition would support teachers in quickly assessing the focus areas of a lesson and determining how it aligns with their educational goals.

The feedback process itself exemplified key aspects of agroecology, such as iterative learning, collaboration, and adaptability. Engaging with the curriculum developers facilitated a two-way exchange of ideas. This collaborative process not only improved the tool's relevance but also fostered a sense of shared ownership.

To ensure a comprehensive evaluation of agroecological education principles, we propose a three-tiered approach encompassing the curriculum, module, and lesson levels.

1. Curriculum-Level Evaluation: At this level, the focus is on assessing whether the overall curriculum effectively integrates the principles of agroecology. This broader evaluation examines the curriculum's design and content to ensure that key agroecological concepts are embedded throughout the entire program. The goal is to answer the overarching question: Does the curriculum as a whole promote and sustain agroecological education?
2. Module-Level Evaluation: This level of evaluation examines whether each module within the curriculum sufficiently incorporates key agroecological principles. For example, in a module consisting of five lessons, the evaluation should ensure that the principles are distributed and represented across different lessons within the module. While some

lessons might focus more heavily on experiential learning (e.g., lessons 1, 2, and 3), others (e.g., lessons 4 and 5) should address principles like farmer-to-student or peer-to-peer learning, as well as communication and awareness. The aim here is to achieve a balanced representation of agroecological principles across the entire module, ensuring that any gaps in one lesson are addressed in others.

3. Lesson-Level Evaluation: While it is not necessary for every lesson to incorporate all agroecological principles, it is essential that each lesson contributes to the overall goals of the curriculum. The lesson-level evaluation ensures that each individual lesson adds value by integrating at least some key principles. This detailed evaluation helps to ensure that no lesson is isolated from the larger agroecological framework, even if it doesn't address every principle directly. Ultimately, each lesson should play a role in building towards the comprehensive inclusion of agroecological principles within the curriculum.

This three-tiered approach ensures that agroecological principles are thoroughly evaluated and incorporated at every level, from the broad curriculum to individual lessons. The feedback and refinement process does not only benefit the current curriculum but also sets a precedent for continuous improvement in agroecological education frameworks. Future feedback process should include a broader range of stakeholders, such as teachers, parents, and students.

Moreover, this evaluation framework is not limited to this specific curriculum; it can be applied to other agroecological or sustainable agriculture curricula to ensure that they align with key principles such as experiential and holistic learning, transdisciplinary approaches, awareness and communication, inclusion and diversity, and farmer-to-student/peer-to-peer learning. This adaptability makes the framework a valuable tool for advancing agroecological education across various contexts and settings.

Conclusion

This study developed and tested a framework for evaluating the Kernza® Educational Curriculum of The Land Institute, using the principles of agroecological education. The evaluation conducted helped highlight the strengths of the lesson and identified areas for improvement. The feedback received from the curriculum developers necessitated a multi-tier evaluation approach – encompassing curriculum, module, and lesson levels – to ensure that it comprehensively integrates the principles of agroecological education. In addition to providing detailed assessment and enhancing the quality of lessons, this framework can also help in the development of a comprehensive agroecological curricula that can, in turn, empower future generations of agriculture leaders with the knowledge and skills needed to support sustainable education, build a more resilient and equitable food system, and solve multidimensional problems in the real-world. Future research should apply this framework in other sustainable agriculture curricula to understand its effectiveness. This could include primary, secondary, and higher education settings, as well as informal education settings such as community programs and agricultural extension services. In addition, longitudinal studies should be conducted to assess the long-term impact on learners' understanding and behaviors related to agroecology and sustainable agriculture, potentially leading to its adaptation to fit different contexts.

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Chapter Four: General Conclusion

In the last few decades, concerns have been growing about climatic and environmental degradation as a result of improper waste management and conventional agriculture. Conventional farming practices often lead to issues such as nutrient leaching, poor manure management, deforestation, and soil erosion (Gomiero, 2015). These problems are a significant cause of environmental degradation and requires innovative solutions. One way to solve this problem is to conduct research on novel methods of farming and waste valorization. In this study (chapter two), I investigated the performance and nutritional composition of BSFL grown on different waste materials. Another way to address this challenge is to equip future professionals with the necessary skills at an early age. To achieve this, I conducted a study (chapter three) to develop a framework for evaluating agroecological curriculum for high school using the principles of agroecological education.

In the first study (chapter two), I explored the viability of using black soldier fly to valorize underexplored waste materials like kernza straw (known for its environmental co-benefits, grain and forage) and spent mushroom substrate, a by-product of mushroom that requires less land to produce, and other widely explored waste materials like food waste and spent coffee grounds into nutrient-dense materials. The results from this study showed that black soldier fly larvae can feed on these waste materials and produce larvae, even though the results varied. Larvae fed on food waste had the lowest larval weight, calcium and phosphorus content compared to other treatments. The mortality rate was lower for larvae fed spent coffee ground supplemented with chicken feed, although this did not differ significantly with other treatments. Larvae fed food waste had the highest FCR compared to those fed kernza-supplemented diets and higher fat contents compared to larvae fed other diets.

The findings from this study indicates that BSFL can be used to valorize various agricultural and food waste into valuable insect biomass, although the performance and nutritional composition may well depend on the type of feed substrate used. In particular, the findings of this study suggest that kernza straw shows promising potential as a substrate for BSFL bioconversion. Kernza, known for its environmental benefits and unique properties, can effectively support BSFL growth and biomass production. This finding has significant implications for waste management and sustainable agriculture and contributes to a circular economy.

In the second study (chapter three), I developed a tool for evaluating the lessons in the kernza education curriculum using principles of agroecological education: experiential and holistic learning, transdisciplinary approach, awareness and communication, inclusion and diversity, and farmer-to-learner/learner-to-learner education. The results from this study showed effectiveness of curriculum developed for agroecological or sustainable agriculture and made recommendations on how to improve lessons designed for sustainable agriculture. Using this evaluation tool, we can develop a comprehensive agroecological and sustainable agriculture curricula that can help train future generations to solve multidimensional problems and effect change in the food system.

Collectively, the findings from this study show that it is important to adopt innovative approaches in education and agriculture to tackle problems of climate change, environmental degradation, and resource scarcity. However, it is important to acknowledge the shortcomings of this study. One significant shortcoming of this study (chapter two) is the relatively small-scale size of the experiments conducted. Another limitation of this study is the limited control of environmental conditions such as temperature, humidity, and lighting as this study tried to mimic real world production of BSFL. Thus, future research should focus on scaling up these experiments to industrial levels to have a better understanding of the economic viability and lifecycle impacts of large-scale production of BSFL. Moreover, because kernza straw is also used as a low-quality ration for livestock, there is a need for further research on the economic viability of feeding kernza straw to traditional livestock as opposed to BSFL. Such research should consider using different supplementation ratios to optimize performance and biochemical composition of the larvae. Cost-benefit analysis comparing BSFL as livestock feed ingredient against other feed sources should also be conducted to ascertain their viability in different agricultural systems.

While BSFL farming holds promise for waste valorization and sustainable agriculture and can be considered agroecological in many aspects, whether it is inherently agroecological depends on how it is implemented in terms of farm scale, resource use, efficiency, social equity, among others. For example, large-scale BSFL farms may cause reliance on monoculture waste streams, which could displace small farms and undermine ecological benefits. Similarly, BSFL farms requiring significant energy inputs for managing environmental conditions or transporting waste materials and centralizing production and profits and limiting access to markets for small farmers could negate the environmental benefits of waste valorization and principles of fairness and participation. Future research should investigate how BSFL farming can be practiced within agroecological frameworks, ensuring that it contributes to biodiversity, resource efficiency, and social equity.

In addition, the feedback process in this study (chapter three) involved only curriculum developers. This oversight limits the study’s ability to fully assess how practical the curriculum is, its reception by learners, and overall effectiveness on the educational community and may result in missed insights that these stakeholders could provide. Future research should explore the long-term impact of this framework on learners' understanding and engagement with agroecology. This will help ascertain the curriculum's effectiveness in understanding agroecology and provide room for refinement to fit local contexts and meet specific needs.

Future research should be channeled into scaling up these practices and educational initiatives. For example, future research should be conducted to investigate the feasibility of using the agroecological evaluation framework developed in this study to evaluate other agroecological or sustainable agriculture curricula. In addition, more studies can be conducted on integrating other stakeholders like teachers, students, and parents in the curriculum evaluation process. On the other hand, large scale research should be conducted to investigate the economic feasibility of feeding kernza straw to black soldier fly as opposed to livestock. Furthermore, research should be conducted on different supplementation ratios of feed substrates used in this study.

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Appendix

Lesson Outline: What is a Grain?

Standards And Objectives

Main Idea

Grains are central to the diets of many people and cultures because they provide key nutrients. Grains' vast presence on the landscape and in human diets provide a huge opportunity to shift our global food system from extractive to regenerative.

Driving Questions

What is the importance of grains in human diets? What effect do grain crops have on human livelihood and ecological well-being?

Lesson Outcomes

Students will be able to:

- List all four major grain types (cereals, pseudocereals, oilseeds, legumes)
- Describe the grains that are part of their daily diets
- Name the significant nutrient categories that grains provide
- Explain why access to diverse types of grains is important for nutritious diets and healthy landscapes

Kansas Family and Consumer Science Secondary Program Standards Link

1.2 Evaluate the nutritional needs of individuals and families in relation to health and wellness across the lifespan.

National Agricultural Literacy Outcomes: NALO Link

T3.9-12.g. Identify how various foods can contribute to a healthy diet.

Lesson Contents

- What is a Grain? Outline and Authorship Document (this document)

For Teachers

- What is a Grain 24-Hour Food Log Rubric
- What is a Grain Assessment Answers
- What is a Grain Classroom 24-Hour Food Log
- What is a Grain Online Resources
- What is a Grain Presentation

For Students

- What is a Grain 24-Hour Food Log Assignment
- What is a Grain 24-Hour Food Log Worksheet
- What is a Grain Assessment
- What is a Grain Vocabulary
-

Teaching What is a Grain?

Lesson Components		
Subject: Food and Nutrition	Grade Level: Secondary	Lesson Time: 1 hour
Supplies Needed: • Assessment • Worksheet • Spreadsheet	Activity type: • 24-hour food log	Links to Resources Used: • Food Calorie Calculator • What the World Eats Website. • Artisan Grain Collaborative

• Assignment sheet • Presentation		
Assessment type: • Pre/Post Assessment • 24-hour food log	What Teachers Should Know: This is a simple lesson. Teachers should find everything they need by reviewing the material.	What Students Should Know: Students should be able to perform basic math and enter information into a Google Sheets document.

Lesson Outline	
Anticipatory Set/Opening: *Learning interest "hook" Opening prompts* *2 min*	*Create a list of food categories that contain grains, i.e., cookies, french fries, gluten-free bread (make sure to include foods made with legumes, pseudocereals, and oilseeds).* *Ask students to stand up every time you read a category containing food they have eaten in the past 24 hours.* *Continue until everyone is standing.*
Methods/Procedures:	Pre-Assessment (5 Min) If you wish to use the assessments, have the students complete it now. Presentation (10 Min) Introduce the topic using the provided presentation. 24-hour food log (15 Min) Have the students follow instructions in the assignment sheet to fill out their 24-hour food logs. They will need

	access to the internet to look up caloric values and the What the World Eats website. Have them spend about half the time filling out individual logs and the other half putting their data into the class Google Sheet and answering the reflection questions. Artisan Grain Collaborative (15 Min) Have students visit the Artisan Grain Collaborative website to answer the last two questions on their worksheets. As students do this, use the data from their 24-hour food logs to fill out the Classroom 24-Hour Food Log. Copy the pie chart from the spreadsheet and paste it into the presentation. This will allow students to see the percentage results without seeing each other's calories. Discussion (5 Min) Compare your class chart to the one on the What the World Eats page. How important are grains to the diets of your class?
Closure and Follow-Up: 5 min	*If you use the assessments, have students complete the post-assessment now.* *Ask students to share one of their reflection questions with the class.*
Additional Activities!	Check out the additional online resources! You can find articles and photography projects that prompt class discussion.

Did you teach this lesson? Tell us about it!

Answer a few simple questions in this feedback survey to help us assess this lesson and create better materials in the future!

Lesson Authorship and Citations

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Quinua (Quinoa) plants near Cachora, Apurimac, Peru

Image in Presentation

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Link

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