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Review
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Review

Edible insects as a means to address global malnutrition and food insecurity issues

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Abstract

Although unconventional in the USA, entomophagy, or the practice of consuming insects, can provide a nutritious relief to many malnourished people in developing countries. Edible insects are part of numerous traditional diets found in over 113 countries, including those in Asia, Africa, and South America. Currently, there are 2 billion people consuming over 2000 recorded edible insects. Many of these worldwide insects contain amounts of protein, fat, vitamins, and minerals comparable to commonly eaten livestock. With the popularity of crickets in both developing and developed countries and the nutrient density of locusts, these insects were of particular interest. Rice flour, made from a major food crop around the world, was used as an effective vehicle to deliver these insect ingredients. The use of inexpensive single-screw cold-forming extrusion technology, due to its capability of high production rate yet low capital and operating costs, was employed in making insect-fortified products. The feasibility of incorporating edible insect flours from cricket and locust in an extruded rice product has been demonstrated to be successful with acceptable shelf stability and sensory characteristics. Nutritionally, the insect rice products developed were energy dense (high fat content) and as an excellent source of protein. They also contained considerable amounts of dietary fibre and iron. Sensory evaluations involving 120 untrained panelists–suggested cricket formulations were well accepted compared with locust formulations. There is a positive outlook on the overall acceptance of entomphagy even in developed countries. As a staple food providing 20% of the world's dietary energy and consumed by over 1 billion people, rice is an ideal vehicle to deliver nutrients carried by edible insects. The incorporation of insect flours in processed foods such as extruded rice products can greatly promote the consumer acceptance by disguising the 'yuck' factor associated with intact insects.

Keywords: edible insect; food security; malnutrition; consumer acceptance; extruded rice.

Introduction

Whether from a perspective of developing or developed countries, the entire global population is in need of alternative food sources. People living in developing nations, including those countries in Sub-Saharan Africa or South Asia, are often found to be dangerously malnourished. With beef and chicken being difficult to come by, they have been enjoying edible insects as a dietary resource for generations. This is because edible insects actually contain several nutritional benefits. They offer plenty of calories, protein, fat, vitamins, and minerals, depending on their species, metamorphic stage, and diet.

Although still widely unconventional, developed countries have also begun considering entomophagy as a means to support our ever-growing populations. In fact, the United Nation's Food and Agriculture Organization (FAO) projects the world population approaching to 9 billion by 2050. As the numbers swell, natural resources such as land and water are being rapidly degraded. Edible insects, with their high feed conversion efficiency and fecundity, as well as their minimal space for rearing, certainly represent as an advantageous solution for present and future food insecurity.

Even so, the 'yuck' or 'disgust' factor is not so easily eliminated from today's cultures. Despite its health benefits, perhaps the unappealing nature of entomophagy is in the consumption of the whole insect. With that, the obscure incorporation of this food source through the utilization of insect flours is considered.

Ongoing studies within our research group at California State Polytechnic University, Pomona have demonstrated the feasibility of the obscure incorporation and fortification of a major food staple, such as rice, by utilizing edible insect flour as a value-adding ingredient. By removing the original form of the insect and incorporating its flour into a food matrix that is widely consumed around the world, we aim to provide an innovative solution for food insecurity and malnutrition, especially in developing countries. Furthermore, the hidden form of the edible insect is designed to reduce the 'yuck' factor and increase the acceptance of entomophagy. Rice flour has been specifically chosen to be the vehicle based on the consideration that the nutrients carried by the edible insect will supplement the nutritional composition of rice. The two main ingredients are combined in different ratios to form a dough mass, which can be processed through an economically feasible, cold-forming extrusion technology. Through this production method, a final rice product containing optimal addition level of insect flours has been developed, and the measurements of its physicochemical properties, nutrient profile, and consumer acceptability via sensory evaluations have been completed. While the measurements of organoleptic and nutritional properties of the insect rice product have been reported in a separate original research article, published with the Journal of Insects as Food and Feed (JIFF-S-17-00032) (Tao et al., 2017), the results of consumer acceptance study are summarized in this review article.

Food Insecurity and Malnutrition

Although not as widespread in the USA, food insecurity remains a serious and prevailing issue for much of the world. There is an estimated 805 million people who are without enough food to maintain a healthy and active lifestyle, according to the World Food Programme (WFP, 2015). Developing countries, especially those in South Asia and Sub-Saharan Africa, have the highest rates of hunger. Although Asia contains the largest population of hungry people, about two-thirds of the total, Africa has the highest prevalence (WFP, 2015).

While many developing countries are facing food insecurity today, Madagascar, for example, is in an especially delicate state. Madagascar is one of the 10 countries with the highest occurrences of chronic malnutrition (UNICEF, 2013). With at least 50% of the population moderately or severely malnourished, food insecurity remains a critical concern in this nation. In 2013 alone, 4 million people faced hunger as almost one-third of the population was burdened with food insecurity (WFP and UNICEF, 2011). Causes of their struggle are numerous and difficult to resolve. Deforestation by slashing and burning, a largely unsustainable agricultural process, has resulted in soil erosion and even rice field destruction (a major staple) (UNICEF, 2001). The fragility of the environment has left very few farmers with enough land to cultivate (UNICEF, 2001). Furthermore, as agriculture accounts for more than one-fourth of the country's GDP and 80% of employment, much of the population has become vulnerable to food insecurity. In addition, since 2009, Madagascar has been facing political unrest, consequently putting the country into further economic distress and leaving almost 80% of the population in poverty (Central Intelligence Agency 2014, UNICEF). Yet another tragedy is the recent locust plague of 2013. As the infestation continues, more food crops and livestock grazing lands could be destroyed, deepening on the suffering of the Malagasy people (FAO, 2009). With these outstanding issues, 53% of rural households have been reported to not consume enough food to maintain an active and healthy life (UNICEF, 2001).

Consisting mostly of rice, vegetables, and tubers, the Malagasy diet involves the consumption of these foods about 4 to 6 times a week. Since rice is the product with the largest production quantity, this is clearly reflected in their diet as it is also the number one commodity available for consumption (FAO, 2014). Yet, proteins, from both vegetables and animals, are seldom eaten, at an estimated rate of 1 to 2 times a week (WFP and UNICEF, 2011). Fat, a major source of calories, has also been demonstrated to be low in their diets (FAO, 2010). Indeed, the main staple meal in Africa consists mainly of cereal grains, such as rice, sorghum, millet, maize, fonio, and tef (Filli et al., 2014). These foods, being composed mostly of carbohydrates (rice 80%, sorghum 74%, and maize 78%), are not a major source of protein, and together with the scarce availability of animal protein, the Malagasy people lack the necessary macronutrients for healthy living (Wu Leung, 1968). Moreover, the WFP and UNICEF (2011) reports only 20% or less of the surveyed children to have received foods rich in vitamins and minerals, sources of which include fruits and vegetables, legumes, nuts, and dairy products. Overall, 84% of households experience inadequate amounts of food or cash every year (WFP and UNICEF, 2011).

Malnourishment occurring in early childhood and if untreated results in life-threatening consequences. Chronic malnutrition will lead to irreversible stunting and has been reported to be the most important risk factor for illness and death from diseases (WFP, 2015; Muller et al., 2005). Approximately 150 million children worldwide do not consume the required amounts of energy or nutrients for growth and development, with more than half (52%) of these children residing in South Asia and almost a quarter (21%) living in Sub-Saharan Africa (UNICEF, 2001).

Nutrient Content of Edible Insects

Interestingly, although perhaps not surprisingly, entomophagy is especially practised in developing nations. Countries in South Asia, where more than 40% of the population is chronically malnourished, have already long accepted entomophagy as part of their culture. For instance, countries such as India and Lao People's Democratic Republic have identified 24 and 21 edible insect species, respectively. Collectively, Africa has been reported to have some 246 species of edible insects. Countries within this continent that exhibit more severe rates of chronic malnutrition, such as Madagascar or Zambia, possess 22 to 33 species (Ramos-Elorduy et al., 1997). These insects are consumed for their comparable levels of energy and nutrients, although the levels may vary depending on species type, metamorphic stage, habitat, and diet. For instance, a study conducted in Thailand demonstrated that 100 g of insects (fresh weight) had comparable, if not more, calories than that of equal weights of commonly eaten livestock, excluding pork (Sirimungkararat et al., 2010). Ramos-Elorduy et al. (1997) reported that of 78 insect species found in Mexico, the caloric content ranged 293–762 kJ per 100 g of dry matter. Specifically, migratory locusts (*Locusta migratoria*), the species of which are currently plaguing Madagascar, were discovered to have calories varying in the range of 598–816 kJ per 100 g of fresh weight in a study conducted in the Netherlands (Oonincx and van der Poel, 2011). Moreover, besides the caloric value, these animals can provide crucial macronutrients as well.

Likewise to the evidence supporting the caloric value of edible insects, it also suggested that insects are considered to be a substantial source of protein. Certain insects found in China were reported with higher protein contents than those in most plants and commercial meat, fowl, and eggs (Xiaoming et al., 2010). In the study, 11 orders of insects were analysed with results of protein contents ranging from a low 13% to a high 77% (dry weight basis). Other researchers reported a range of 37%–54% protein content in eight insects found in Thailand (Raksakantong et al., 2010). In spite of these variations in protein content, edible insects overall demonstrate to be an exceptionally good source of protein. While this macronutrient is often difficult to obtain in developing countries and so is lacking from their daily diets, edible insects are relatively more available than other meats, demonstrating yet again its worth as a solution for reducing global food insecurity.

Furthermore, while malnutrition is not limited to protein deficiencies but includes the overall lack of caloric intake, populations within developing countries could also benefit from energy dense foods provided by edible insects (DeFoliart, 1992). Energy intake can be greatly enhanced, to an extent, with higher levels of fat, like those potentially found in edible insects. In a study lead by Womeni and others (2009), six insects from Cameroon of Sub-Saharan Africa were analysed to determine their lipid contents and essential fatty acid profiles. Results showed that not only were these insects an excellent source of fat, ranging from 9.12% to 67.25% (dry weight basis), but also that they were rich in polyunsaturated fatty acids. These types of fats, along with monounsaturated fats, have been widely accepted to offer more nutritional benefits and should be used to replace the intake of saturated fatty acids (Yang et al., 2012; Enos et al., 2014). Furthermore, the polyunsaturated fats included essential fatty acids, such as linoleic (omega-6) and linolenic (omega-3) acids (Womeni et al., 2009). Comparable findings were demonstrated in Thailand as well, varying between 0.34% and 23.98% of total fat content depending on the species of insects (Raksakantong et al., 2010). Thus, edible insects have the potential to be an exceptional source for energy and macronutrients.

Micronutrients, on the other hand, are just as essential for a healthy life. A major concern for developing countries is iron intake as its deficiency is the world's most common and widespread nutritional disorder (WHO, 2014). Many of the insects safe for consumption contain abundant levels of iron that often exceed other commonly eaten animals. For instance, edible insects such as the popular palm weevils (*Rhynchophorus phoenicis*) or mopane caterpillars (*Imbrasia belina*), both species found in Africa, can provide 12 and 31 mg of iron per 100 g of weight, respectively (Banjo et al., 2006). Chicken and beef, on the other hand, provide only 1.2 and 3 mg of iron, respectively (Sirimungkararat et al., 2010). Zinc, another mineral important for growth and development, can be generally found in most insects. For example, it has been reported that the aforementioned palm weevil larvae contain 26.5 mg per 100 g (Bukkens, 2005).

Entomophagy—More Than Survival

The overall nutritional value of edible insects presents them to be a remarkable alternative for alleviating the food insecurity and malnutrition in developing countries. Although it could be said that the underprivileged do turn to edible insects for sustenance since other forms of livestock are either unavailable or expensive, the tradition of consuming edible insects is not always a tactic for survival. Banjo and others (2006) reported edible insects being included in a planned diet throughout the year and not solely as an emergency food supply. A collective group of people in South Africa called Pedis, for instance, value insect meals, such as those derived from caterpillars, even more so than beef as the latter sales decrease during caterpillar harvesting seasons (Womeni et al., 2009). Palm weevils, especially the larvae form of *R. phoenicis*, have been a part of a traditional African diet for centuries and are, like the locusts there, prepared by frying (DeFoliart, 1993; Banjo et al., 2006). Besides Africa, this insect has also been appreciated across other tropical regions including Latin America and Asia (DeFoliart, 1993). In Mexico, investigators reported exceptional consumer acceptance for their maize flour tortillas supplemented with ground yellow mealworm larvae (*Tenebrio molitor*) (Aguilar-Miranda et al., 2002). The practice of eating insects can also be found in the East. *Lethocerus indicus*, or giant water bug, is a particularly popular insect consumed throughout several Asian countries such as Thailand, Laos, Vietnam, and Cambodia (Kiatbenjakul et al., 2015). Its odour provides a flavour profile that is essential for consumer acceptance of food products such as chili pastes or fish sauces. As entomophagy is practised around the world, a novel edible insect product has certain potential for being accepted and enjoyed.

Nutritional Variability of Edible Insects

However, it is important to note that while promising, edible insects are still highly variable between/within species and metamorphic stages. When comparing the amount of energy found between edible insects in previously cited studies, these values varied by hundreds of calories per gram (Ramos-Elorduy et al., 1997; Oonincx and van der Poel, 2011). Protein content had differences as great as 64%, whereas fat had variations as high as 44% (Womeni et al., 2009; Raksakantong et al., 2010; Xiaoming et al., 2010). It could be easily discerned from these values that the benefits of each edible insect species can vary significantly. In addition, analogous to shellfish or prawns, the type of habitat and diet of these insects can also change their flavour and even their nutritive values (Ramos-Elorduy et al., 1997; Klasing et al., 2000; Finke, 2003; Raksakantong et al., 2010; Oonincx and van der Poel, 2011; Nowak et al., 2016). As grasshoppers (*Zonocerus variegatus*) in Nigeria were fed with bran, which contains more fatty acids than that of corn, these insects demonstrated almost doubled protein levels (Ademolu et al., 2010). In yet another study, migratory locusts were fed with three different diets, consisting either solely of grass, mixed grass and wheat bran, or combination of grass, wheat bran, and carrots (Oonincx and van der Poel, 2011). The investigators found the wheat bran diets reduced the protein content and increased the fat content of the locusts, whereas the addition of carrots further enhanced the fat content and provided greater levels of β-carotene. Hence, although entomophagy has been revealed with great potential to be an extraordinary resource for relieving global food insecurity and malnutrition, it is essential to obtain complete nutritional profiles in order to determine the actual nourishment available in the finished product.

Environmental and Economic Impacts

While developing countries are currently facing the burden of food insecurity, the FAO (2009) predicts that the global population will increase to 9 billion by 2050. As the world population proliferates, the demand for food and feed will escalate along with it, subsequently requiring food production to increase by 70% (FAO, 2009). With the current state of the environment, and as it continues to degrade, there is a call to conserve natural resources such as land and water. Evidently, rearing insects requires remarkably less land than farming other categories of livestock. Oonincx and de Boer (2012) discovered that to produce 1 kg of edible protein, mealworms (*T. molitor*) required only 10% of the land that is needed for beef production. Although this difference may not be as dramatic when compared with pork or chicken production, mealworm farming still requires 29%–50% less arable land. Due to their obvious smaller size, edible insects also have the potential to be farmed vertically, thereby requiring no additional land clearing to advance production (van Huis et al., 2013). Greenhouse gases, including carbon dioxide, methane, and nitrous oxide, are also produced at a lesser rate by insects such as crickets (*Acheta domesticus*) and mealworms (*T. molitor*). When compared with pigs and cattle, the difference is by a factor of about 100 (Oonincx et al., 2010). Furthermore, the manure produced from common livestock also contaminates the surface and groundwater while releasing ammonia and acidifying the land (van Huis et al., 2013). Although pigs have demonstrated to produce ammonia at a rate of 10 times or greater than crickets and mealworms, the quantity produced by cattle is undoubtedly even less favourable (Oonincx et al., 2010).

As land becomes scarce, the water supply is equally threatened. The FAO (2013) predicts that by 2025, two-thirds of the world will be under stress due to water shortages. When evaluated against the quantity required to produce 1 kg of grain protein, 100 times more water is required to produce the same weight of animal protein, especially as water is necessary for forage and feed production (Chapagain and Hoekstra, 2003). Although assessments for the quantity of water required for farming edible insect is currently unavailable, the results are likely in favourable directions, in parallel with that of greenhouse gas and ammonia emissions.

In addition to the heavy usage of land and water, farming livestock also requires feed, which in turn requires further land clearing. Alternatively, insects are cold-blooded and so only require feed for energy and warmth. Studies have shown that to produce 1 kg of livestock weight, at least 2.5 kg of feed is required for poultry meat, 5 kg for pork, and 10 kg for beef (Smil, 2002). Edible insects, such as crickets (*A. domesticus*), require only 1.7 kg to produce the same weight (Collavo et al., 2005). In addition, only a percentage of this livestock weight is edible, consequently reducing the actual production and availability of meat protein and other nutrients. While chicken and pork provide 55% of edible weight, beef only provides 40% (Nakagaki and DeFoliart, 1991). Crickets (*A. domesticus*) conversely offer 80% of its live weight for consumption, making its feed conversion efficiency exceptionally high. Furthermore, insects in general reproduce more rapidly and in greater quantities. For instance, the same aforementioned cricket species can lay 1200–1500 eggs within 30 days (Patton, 1978). Insects also reach their adult stages much quicker than their livestock counterparts and so are capable of reproduction sooner.

Getting Over the 'Yuck' Factor

However, despite the undeniable benefits for consuming and rearing edible insects, this does not deter from the 'yuck' or 'disgust' factor. A study conducted by Rozin and others (1999) revealed that despite American students being willing to touch insects with their hands, many declined touching those insects to their lips. The concept of food neophobia, the fear of trying new or novel food products, has been suggested as the reason for this rejection (Megido et al., 2014). This concept is explained by Rozin and Fallon (1980) to be a dismissal due to distaste for the organoleptic qualities, fear of danger to the body, or disgust stemming from a prior impression of what the product is or of its origin. While either of these three explanations or the combination thereof may be understandable, perhaps the neophobia of entomophagy could be lifted. Lobster, once considered 'junk' food in the 17th and 18th centuries, was established to be cruel and unusual punishment for feeding to servants and prisoners more than twice a week (Greenlaw, 2002; Crowley, 2015). Today, lobster is regarded as a fine dining food, depicted as a pleasure enjoyed by consumers with high incomes. Another interesting example is the history of the ever popular sushi dish, the California roll. When first introduced in Los Angeles, Ichiro Mashita, the sushi chef of Tokyo Kaikan, innovatively substituted the toro (fatty tuna) with avocados as it had a similar texture but was more familiar to Americans. He also placed the nori inside the rice as this too was an unusual ingredient (Crowley, 2015). Presently, California rolls have become an icon of sushi and are enjoyed all across the globe. Whatever the cause of the prior neophobia, lobster and the California roll have had their status momentously and positively changed. Edible insects have the same potential. Megido and others (2014) suggest that the promotion of knowledge and acceptance of edible insects will begin with the understanding of the relationship between insects and shellfish, as they are simply arthropods of the land and sea, respectively. Correspondingly, increasing the frequency of positive exposures and tasting trials would also be effective.

Edible Insect Fortification in Rice Flour via Extrusion Technology

What is also proposed for increasing acceptability is the form of the edible insect ingredient. While traditional cooking methods such as roasting or frying are frequently used to prepare tastier or more palatable dishes, the insects often remain whole, especially in tropical regions (van Huis et al., 2013). Instead, edible insects can be made into granular or paste forms that may result in improved acceptability. While in a paste or powder form, they can be incorporated into other foods. For instance, in Thailand and other South Asian countries, ground giant water bugs (*L. indicus*) are an essential ingredient in chili paste and fish sauces (Kiatbenjakul et al., 2015). Although the chili paste is used as an ingredient in dishes, the current study suggests that the fortification of a main staple food could be more effective as the ultimate vehicle for delivering valuable nutrients offered by edible insects.

Rice is a staple food for more than half of the world's population, especially in developing countries (IRIN, 2010; USDA, 2012). It provides 20% of world's dietary energy and supports the livelihood of more than 1 billion people (FAO, 2004; IRIN, 2010). It is regularly consumed and composes a great portion of the diets in both developing and developed countries. The overall percent of dietary energy supplied by rice for Asia, Africa, and South America has been reported to be about 30%, 10%, and 10%, respectively (FAO, 2004). Specifically, developing countries such as Bangladesh, Laos People's Democratic Republic, and Indonesia have more than half of their dietary energy supplied by rice. Other than energy (363 calories/100 g), rice is also a good source of thiamin, riboflavin, niacin, and amino acids such as glutamic and aspartic acid (FAO, 2004). While rice lacks lysine, edible insects such as caterpillars (*Gynanisa* *maja*), grasshoppers (*Ruspolia differens*), and winged termites (*Macrotermes falciger*) can complement this essential amino acid (Siulapwa et al., 2014).

To obtain rice, the grain is milled to remove the outer husk and bran layer. During this process, broken rice is produced and can be used to create rice flour. Our research group has conducted a study to determine the feasibility of combining an edible insect flour ingredient with rice flour for the fortification of a staple food (Tao, 2016). The successful results from this study would first extend the yield of rice harvest and create an additional economic prospect for this milling byproduct (Qian and Zhang, 2013) and second improve the acceptability of a nutrient dense ingredient such as edible insects for general consumers.

To create this fortified rice product, extrusion, a method that is growing in popularity especially in developing countries, was employed. Extrusion is a continuous process that combines cooking, mixing, shaping, and forming (Fellows, 2009). The process begins by the raw materials, typically in granular form, being fed into the barrel where water is added to convert the dry ingredients to a semi-moist dough mass that is processed further. As the screw within the barrel kneads the mixture, it becomes plasticized with a desirable rheological property suitable for extrusion. The screw pushes the dough mass out of the die holes where it expands and cools rapidly, forming the shape set by the type of die plate used. This type of technology can generate a remarkable number of products, ranging from cereals, pasta, soup and beverage bases, hot dogs and sausages, processed cheese, and chewing gum (Fellows, 2009).

Action towards promoting the application of extrusion technology has already been set forth. ExtruAfrica, an initiative of the Center of Excellence in Advanced Manufacturing at the North-West University in South Africa, encourages the extrusion method through conferences and training workshops. The first seminar was first held in 2011 and continues on (ExtruAfrica, 2015). Filli and others (2014) suggest extrusion technology to be a key to adding value to agricultural commodities to reduce food insecurity in developing countries. Staple cereal grains, including rice, have yielded positive results. In fact, several investigators have already made considerable progress in creating products that incorporate indigenous materials through extrusion applications (Filli et al., 2014) while increasing nutrient density (Obatolu, 2002). Moreover, utilization of extrusion technology will also offer potential employment and an improved livelihood for local citizens.

Consumer Acceptance of Insect Fortified, Extruded Rice Product

As detailed experimental design and laboratory measurements are presented in a separate research article published by Journal of Insects as Food and Feed (JIFF-S-17-00032) (Tao et al., 2017), this review article will mainly report the outcomes from a consumer acceptability study.

To make the extruded insect rice product, two edible insect flours were chosen, derived from cricket and locust, respectively. Both insects are enjoyed by many populations around the world. Crickets are commonly consumed in Thailand, where there are 20 000 registered cricket farmers (van Huis et al., 2013; Dunkel 2015) as well as other Asian countries such as Lao People's Democratic Republic and Cambodia (van Huis et al., 2013). They are also making their way into the US market as they are appearing in commercially produced products such as energy bars from Chapul (Colorado) and 'Chirps' (cricket chips) from Six Foods (Boston, MA). Nutritionally, per 100 g, crickets can offer 125 kcals, 15 g protein, 6.3 g fat, 41 mg iron, and 75 mg calcium as well as other benefits (Sirimungkararat et al., 2010). Crowley (2015) stated that crickets provide 15% more iron than spinach, two times more protein than beef, and equal quantity of vitamin B12 as salmon. Locusts, while currently not as available as crickets in the market, are superior in nutrient density. They can offer 598–816 kcal, 13–28 g protein, and 8–20 mg iron per 100 g (Oonincx and van der Poel, 2011; van Huis et al., 2013). Inclusion of locust may also provide a solution to present or future infestations, as these insects often occur in swarms. Despite being viewed as pests, locusts are popular as fried dishes in countries such as Thailand and Madagascar.

Brown rice flour was used as the major bulk ingredient for the production of the extruded insect rice. In contrast to white rice flour, brown rice flour is more nutritious and also provides the colour background to disguise the intrinsic dark colour from edible insects. Brown rice flour offers an additional 18% protein, 48% dietary fibre, 82% iron, and 67% zinc compared with its white colour counterpart (USDA, 2015—National Nutrient Database for Standard Reference, Release 27). In general, white rice is also inferior in its supply of vitamins and minerals when compared with brown rice.

Formulation development began at a 5% (dry weight basis) addition level of insect flour in the extruded rice formulation and was then increased to 10% and 15%. Concerns for the increasing addition levels of edible insect ingredients included an intensified aroma and taste, which, although may be familiar in other dishes, is not currently associated with rice. Regardless, the protein fortification of insect flour to a product such as brown rice was certainly advantageous. For instance, by referencing the certificate of analysis (COA) provided by the vendor of the cricket flour, we predicted that a 15% insect flour formulation would theoretically increase the protein content by 8.5–9 g of protein per 100 g of insect rice. Together with the protein content originally in existence with brown rice flour (3 g protein per 40 g serving), 100 g of the insect rice would provide an estimated 13.5–14.6 g of protein or 26%–29% of the daily value (DV) of protein.

A preliminary study confirmed that there were no major differences observed from both the extrusion process and the physical and organoleptic properties of the extruded rice particles when incorporating 5% cricket flour in the brown rice formulation; however, the incorporation of 10% and 15% resulted in apparent difficulty to the extrusion operation and observable differences in particle shape, size, and organoleptic properties. Therefore, the study later focused on the formulation development using higher addition levels (10% or 15%) of either cricket or locust flour. A total of four formulations were developed: 10% cricket rice (10CR), 15% cricket (15CR), 10% locust (10LR), and 15% locust (15LR).

To determine the acceptability of the insect rice product, a panel of 120 untrained participants were recruited via convenience sampling. Panelists were required to be without shellfish allergies, consumers of brown rice, and between the ages of 18–65 years old. It was heavily stressed that those with shellfish allergies were unable to partake in the study as an allergy to shellfish was likely to produce a similar reaction to land insects. It was also encouraged that the participants were either familiar with or enjoyed brown rice as this was the base of the products. With the questionnaire being an affective sensory test, it was essential that the panel be users of this product. The age range of the participants was determined as a means to exclude minors and those with a higher risk of compromised immune systems. Another prerequisite for participants was that they were willing to consume edible insects. Thus, participants knew that the products to be tasted contained such an ingredient. Although the 'yuck' factor remains a major issue in entomophagy, those who unknowingly consumed edible insect products could become seriously distraught after learning what they've tasted. Hence, despite the potential bias that may occur from having this information, it was in the best interest of the participants that they were informed that the products contained edible insects.

Sensory Panel Demographics

To profile the sensory panel, a demographics survey was included in the questionnaire and the age, gender, ethnicity, and the highest level of education were asked (Figures 1–4).

With recruitment taking place on the university campus, it was no surprise that the majority of the panel was in their early 20s, about 76% (Figure 1). Only 6% of the panel was 35 years old or above. It was also found that the ratio of men-to-women panelists was almost 50:50, with only 10% more females to males (Figure 3). In a previous study conducted in Belgium, a similar ratio was found in their sensory evaluation with mealworms (*T. molitor*) and crickets (*A. domesticus*) (Megido et al., 2014). These similarities may suggest that either entomophobia or lack thereof holds no discrimination against gender, although this may require further analysis of the data to confirm this proposition. In terms of ethnicity, there were a greater number of Latinos and Asians, together making up almost 70% of the sample population (Figure 2), which may simply be reflective of the campus population. An issue, found only after surveys were conducted, was in the options available for the education-level question. There was no option for participants to identify themselves as persons who have graduated from their bachelors but were not pursuing any further education at the time. For instance, there were no choices for completing a 2- or 4-year degree while currently in the workplace and not continuing any education. There was also no option for those who were still in school but past their 4th year of college. With that, there may be some inflation within the data for the groups stating to be within their 1st–4th year in college (Figure 4).

Perception of Entomophagy

Several inquiries pertaining to the concept of entomophagy were asked in a separate survey within the questionnaire. These questions and their responses are displayed in Figures 5–8. As mentioned, two of the largest ethnicity groups within the sample population were Latinos and Asians. In Mexico, 'escamoles', or black ant larva, are fairly popular dishes and can cost $25 or more per plate (Aguilar-Miranda et al., 2002; Premalatha et al., 2011). 'Ahuahutle' is a famed

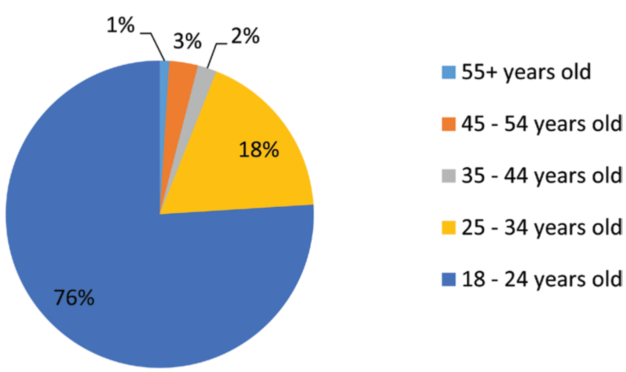

Figure 1. Age of sensory panel.

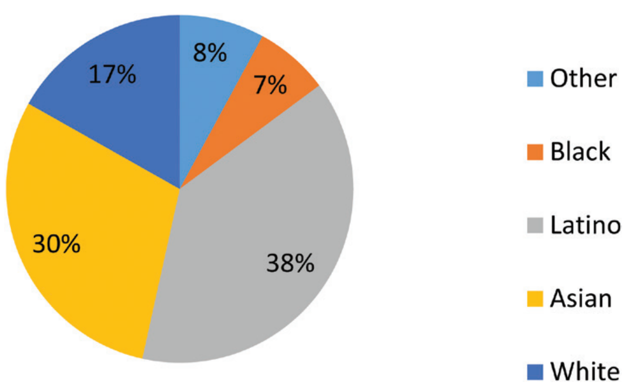

Figure 2. Ethnicity of sensory panel.

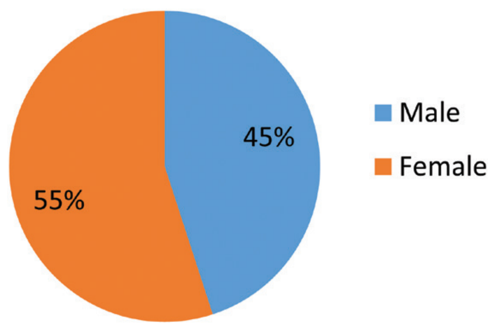

Figure 3. Gender of sensory panel.

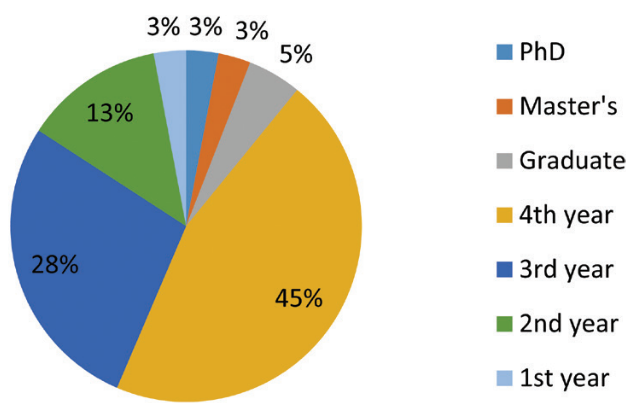

Figure 4. Education level of sensory panel.

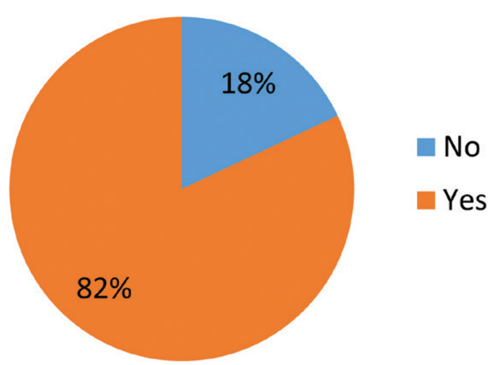

Figure 5. Familiarity with entomophagy.

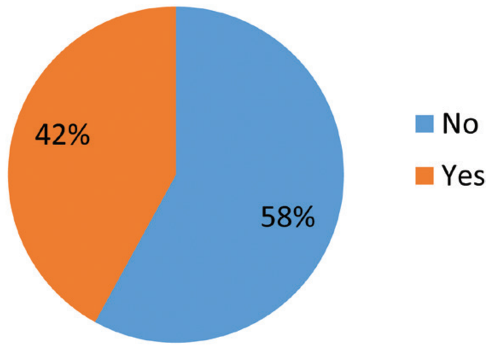

Figure 6. Experience with entomophagy.

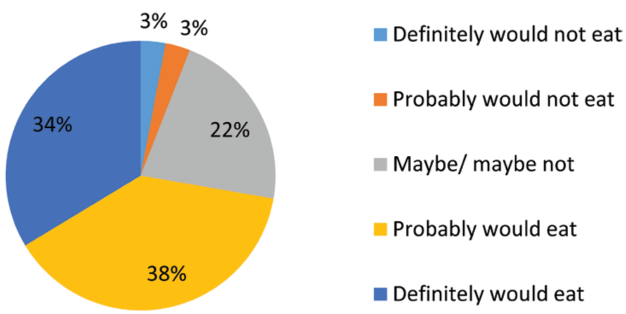

Figure 7. Future willingness to consume edible insects.

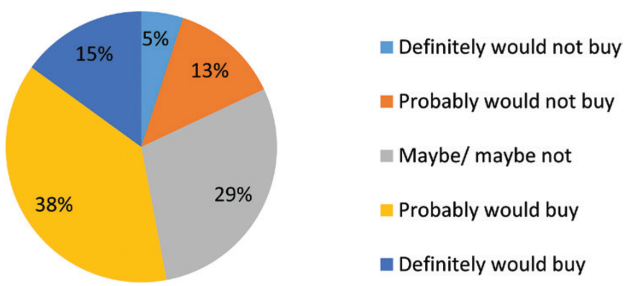

Figure 8. Future willingness to purchase edible insect products.

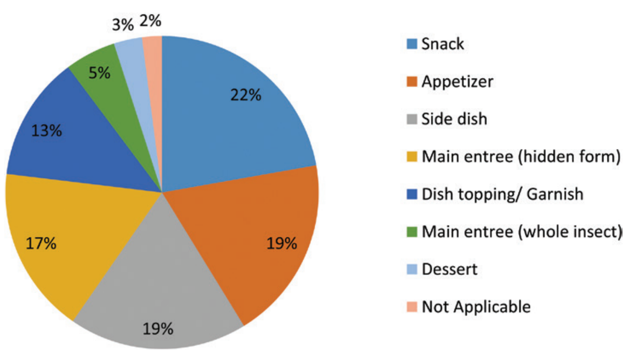

Figure 9 Perception of edible insects in the diet.

Mexican caviar that is composed of some seven different species of Hemiptera (true bugs) (DeFoliart, 1992; Aguilar-Miranda et al., 2002; van Huis et al., 2013). A perhaps even more famous food, especially in Oaxaca, Mexico, is 'chapulines', or grasshoppers, and is consumed as street food (van Huis et al., 2013). This particular dish can be found in many Mexican restaurants in the USA.

While entomophagy is unquestionably strong within Latin America, countries in Asia also share this tradition. The giant water bug, as aforementioned, is a prominent edible insect used in multiple dishes for its unique flavour in Thailand and other South Asian countries (Sirimungkararat et al., 2010; van Huis et al., 2013; Kiatbenjakul et al., 2015). While silkworms are farmed for silk production, their pupae are also prized delicacies in China, Japan, Thailand, and Vietnam (Sirimungkararat et al., 2010; van Huis et al., 2013). In Korea, rice-field grasshoppers are consumed as side dishes or snacks (van Huis et al., 2013). Considering that about 70% of the participants were self-reported to have cultural or ethnical background from countries where entomophagy is such a widely practice custom, it seemed appropriate that at least these many participants were familiar with the practice of consuming edible insects (Figure 5). Furthermore, as the said countries are all regarded as developing nations, the data collected from the sensory evaluation study could be somewhat extrapolated to provide indications of consumer acceptance of such insect products in those countries within Latin American and Asia, although domestic Latin Americans and Asian Americans may practice unique dietary habits that are more or less different from the customs found in their mother nations. Thus, despite the present investigation being unable to reach those currently living in countries such as Mexico or Laos People's Democratic Republic, the results could still offer some implications for such products being implemented in developing countries in the future, although these generalizations may be fairly limited.

Together, the 82% of panelists being familiar with entomophagy and the 73% of participants declaring a high probability of consuming edible insects in the future (Figure 7), which pointed towards a positive trend. In a separate study, Tuorila and others (1994) found a positive relationship between pleasurable first experiences with a novel food and the likelihood of future consumption. As more than 50% of the free-response comments included a statement of their enjoyment and/or support of the current study and its products, this certainly presents a progression towards the future applications of edible insects in the market, even in developed nations. Although it was required that participants be willing to consume edible insects to taste the samples, it cannot be completely assumed that the participants would have chosen to eat edible insects after this experience. This is clear within the 6% who reported that they probably would not or definitely would not consume edible insects in the future. This unwillingness could imply that there was some other incentive for their participation in this particular project. This could include some potential extra credit offered by their professors or even the peer pressure from friends and classmates.

Even so, the majority of the participants were willing to consume edible insects in the future. While 73% reported positively in this inquiry, only 42% were able to say that they had consumed edible insects before their involvement in the current study (Figure 6). With more participants (58%) never having previously consumed edible insects, this is certainly a positive outcome of the study. It demonstrates the eagerness of a population to at least try edible insects. Even more dramatic are the findings from the Belgium study by Megido and others (2014). In this particular survey, the researchers found that although 46.6% of the participants reported some negative attitude towards entomophagy, an even greater number of respondents, 77%, were willing to consume edible insects. The novelty, and perhaps curiosity, of entomophagy may be even more powerful than the 'yuck' factor. Progress is being made towards the acceptance of entomophagy, much like sushi and lobster in the USA.

On the other hand, when taking into account the willingness to purchase edible insect products in the future, there seems to be some disparity. Although people stated that they would probably and definitely consume edible insects in the future, the results from Figure 8 show that they may not actually purchase these insect products. It is proposed that this is somewhat correlated with the fact that the majority of the panel is college students with limited finances, where money is only spent on items that are absolutely essential or worth the expense. As mentioned in the free response portions of the questionnaire, knowing of the nutritional and environmental benefits of consuming and farming edible insects would likely provide enough information for these consumers to make a decision towards purchasing edible insect products in the future.

An inquiry pertaining to the opinion of how edible insects should be placed in the diet was also included in the survey. Participants were asked to select as many choices as they felt that described their opinions. Perceptions of edible insects in the diet are displayed by the percentage of the sensory panel who selected those choices. This particular survey question had multiple selections and participants were asked to select all that applied (Figure 9).

When considering the marketing of edible insect products, the results from Figure 9 suggested that edible insects are most often preferred to be consumed as a snack (22%), appetizer (19%), and side dish (19%). Edible insects being perceived most as a snack could be related to their small sizes or, in general, that snacking is on the rise. In fact, in 2014, the number of in-between snacks increased to 2.8 with more than half of adults consuming three or more snacks per day (Wyatt, 2014). In a previous study, although 'snack' was not included as an option in the survey, edible insects were primarily distinguished as an appetizer. Investigators suggest that this also be due to the small size and original form of the food (Megido et al., 2014). With edible insects being perceived as fourth as a main entrée (17%) in the current research, this implies that this source of protein is primarily viewed as only supplementary and not yet as a main source of meat, such as those from beef or chicken. Edible insects were even less identified as a main entrée if it were left in its whole form and as a dessert. While people generally do not consume their meat as whole animals, this is no surprise to be the same for insects. Even with shellfish, such as with shrimp, many consumers may prefer to have the head removed before consuming. Moreover, as edible insects are not particularly sweet, it is unlikely that edible insects would be perceived as dessert unless people were familiar with the chocolate-covered insects or insect lollipops already available on the market. Even so, comparing these results with the response pertaining to the panels' personal accounts with entomophagy, it was also derived that a few previous experiences with edible insect candies were not positive ones. With these negative experiences, it seemed appropriate that the 'dessert' option was not as highly selected even with the familiarity of edible insects as candies.

As mentioned, personal accounts of entomophagy were included as a free response question in the survey (Tao, 2016). A total of 50 people out of the 120 panelists provided their own encounters with edible insects. Of these experiences, there were an unanticipated number of accounts where the insect was intact. These foods were mostly roasted, fried, or seasoned products and were implied to be consumed as snacks, appetizers, or side dishes. About 20% of the experiences were either in Mexico or in Mexican restaurants and involved grasshoppers. However, an overwhelming majority of the experiences was with crickets (86%) and was followed by worms (i.e. such as mealworms, maggots, or silkworms) being the second most consumed insect (32%). While some enjoyed their experiences, several panelists stated that consuming whole insects was a bit off-putting but suggested that if the flavour was suitable, they would be more likely to enjoy the product. This comment about flavour being able to better allow the acceptance of a product was also reflected in the actual sensory evaluation on four attributes including colour, aroma, taste (flavour), and texture (mouthfeel), as presented with more details in the separate article published by Journal of Insects as Food and Feed (Tao et al., 2017).

Summary of Sensory Evaluation

Besides the four attributes being considered by the panelists based on a 5-point 'Just About Right' (JAR) scale, participants were also asked to rank the four insect rice formulations on overall liking based on a 7-point hedonic scale from 1 = dislike extremely to 7 = like extremely. Among the four sensory attributes, colour and aroma were not the key factors blocking participants' acceptance of the insect rice products, whereas flavour (taste) and texture (mouthfeel) were significant in differentiating the panel's overall liking between two insect flours (cricket vs. locust) and two addition levels (10% vs. 15%) employed in the rice formulations. Of the flour insect rice formulations, lower insect formulations, e.g. 10CR and 10LR, were observed to be more parallel to market brown rice in flavour and mouthfeel, whereas the rice products made with cricket flour (10CR and 15CR) were more preferred over those made with locust flour (10LR and 15LR) in all sensory attributes, except the colour. This is because locust flour featured a 'golden brown' colour shade to the rice products, whereas the incorporation of cricket flour resulted in some 'greyness' to the extruded rice particles.

Even so, flavour remained an important component to the acceptability of the insect products as several participants mentioned that a suitable flavour could positively sway the overall opinion of a product. Multiple criticisms made by the panel recommended that the acceptability of the products would be greatly improved if served alongside other foods or seasoned, such as with salt or soy sauce. As aforementioned, the study conducted by Megido and others (2014) involving sensory evaluation on mealworms (*T. molitor*) and crickets (*A. domesticus*), where these insects were prepared in a variety of ways including baked, boiled, a crushed mix of both insects, mealworms flavoured with vanilla, and mealworms with chocolate. It was found that the most accepted form of preparation was with chocolate, followed by flavoured with paprika, and then baked. Although each mealworm was crispy in texture, the investigators advocate the flavour to be the factor in preference (Megido et al., 2014).

By being a rice product, these insect formulations do have the advantage of being versatile in their formulation and preparation. Indeed, one of the research assistants in our group took it upon himself to create a kimchi fried insect rice dish that was very much well received by the other investigators in the group. While this sensory evaluation reveals some introductory indication of how this product would be fairly accepted in a developed country, such as the USA, the insect rice has the potential of being further developed to include flavours from herbs, spices, etc. Another potential ingredient aforementioned is the introduction of cocoa powder. Relating the colour observed in 10LR, which was with a toasted brown hue, many participants expected it to be much more flavourful than actually experienced. In utilizing cocoa powder, and presenting the succeeding outcome as a chocolate product, this could reduce the misleading nature of the brown colour derived from the locust flour. Besides some colour matching/masking, the cocoa powder may provide some improved flavouring as a chocolate ingredient. The possibility for the research and development of this insect rice into a marketable product is seemingly boundless.

Conclusion

While fortifying an under-utilized resource with a nutritionally dense ingredient, development of this edible insect rice product innovatively answers the call to reducing food insecurity and malnutrition in developing countries. Moreover, this study can further serve as a platform for further exploration in incorporating other various edible insect ingredients and staple foods.

Nutritionally, the insect rice formulations that we developed have shown much promise as a solution to global food insecurity. With 10–12.5 g per half cup serving and 20%–25% of the DV, the cricket and locust rice products were confirmed to be excellent sources of protein. Furthermore, the insect products demonstrated to offer 150%–200% more protein than market brown rice. Future studies in identifying the amino acid profile would yield even more valuable information concerning the nutritional benefits of edible insects.

From the fat analysis results, the insect formulations provided 10%–12% DV for fat (6 g in 10% formulations and up to 7.7 g in 15% formulations) when one serving of ½ cup or approximately 80 g of such rice products were consumed. Although the fat content may be relatively high for American consumption, this created an energy dense food that is rather preferred in developing countries. Products such as the insect rice could help us alleviate the hunger being experienced in countries such as Sub-Saharan Africa and South Asia as the population in these countries continue to undergo serious protein-energy malnutrition diseases.

Protein-energy malnutrition is the most critical nutritional issue faced by populations in Asia, Latin America, and Africa, especially in children (Latham, 1997). Perhaps of the most infamous and severe cases of the malnutrition emergencies are marasmus and kwashiorkor. While marasmus is simplified to be caused by the overall deficiency of food, kwashiorkor is caused by lack of energy and protein as the diet is primarily composed of carbohydrates. The former results in the dangerous wasting of the body as fat and protein stores are utilized to create energy to survive. People inflicted with kwashiorkor, on the other hand, result in serious oedema along with wasting. As the many populations within developing countries are already practising entomophagy, the novel insect rice products can naturally offer a supplement to the plain rice staple within their diet. As demonstrated by our study (Tao, 2016), the insect rice can provide not only 150%–200% times more protein, but overall increase the caloric intake for these starved people. In comparison to typical brown rice, the insect rice products can provide upwards to 58 more of much needed calories. The insect rice is also highly likely to provide other added advantages, such as increased uptake of iron and dietary fibre.

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