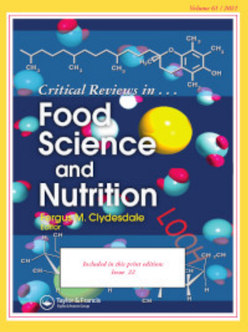

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REVIEW

Fatty acid profile, minor bioactive constituents and physicochemical properties of insect-based oils: A comprehensive review

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ABSTRACT
Insect-based food or ingredients have received tremendous attention worldwide because of their potential to ensure food and nutrition security, mitigating the reliance on land-dependent agricultural products. Indeed, insect-farming has low environmental impacts with reduced land, water and energy input. More importantly, insects are rich in high quality proteins and fats. They are also excellent sources of minerals, vitamins and bioactive compounds. Insect-based lipids are intriguing because they may contain high levels of unsaturated fatty acids particularly linoleic and α-linolenic acids. Besides, the insect-based lipids also show a considerable amount of bioactive components such as tocols, sterols and carotenoids. However, their fatty acid compositions and the nutritional values may vary depending on species, feed composition, developmental stage, geographical locations, and extraction techniques. Therefore, the present article aims to provide a comprehensive review on the fatty acid composition, the minor bioactive constituents and the physicochemical properties of fats and oils derived from insects of different orders (Coleoptera, Lepidoptera, Hymenoptera, Orthoptera, Hemiptera and Diptera). The various parameters affecting the nutritional compositions of the insect-based lipids will also be highlighted. These information will definitely provide a detailed insight on the potential applications of these fats in various food systems based on their unique properties.

KEYWORDS
Insect lipid;
fatty acid compositions;
mealworm; red palm weevil;
silkworm; honeybee;
locust; melon bug;
black soldier fly

Introduction

Entomophagy or the consumption of insects has been adopted since the prehistoric time with more than 2000 documented edible species (Tang et al. 2019; van Huis 2013). Recently, the practice of eating insects has gained attention globally owing to the excellent micro- and macronutrient levels of the insects. Moreover, the insects are considered as "green" and sustainable food sources. A recent report discloses that the edible insect market is forecasted to grow at a CAGR of 26.5% and reach $4.63 billion by 2027 (Research & Markets 2021). It can be seen when the insect-based food products such as cricket flour pasta, cricket chips, beetle beers, mealworm-based cooking oil and others are legally commercialized and widely publicized throughout the global market (Cicatiello et al. 2016; Collins, Vaskou, and Kountouris 2019). In fact, insects show a high protein and fat content, ranging from 40 to 75% and 20 to 40%, respectively. The quality of insect-based protein is comparable and sometimes superior than the animal-based protein in term of amino acid composition. The insect-based protein has a high digestibility (76 – 96%) and can satisfactorily provide almost all essential amino acids in an adequate level for adults as recommended by World Health Organization (WHO) (Tang et al. 2019; WHO 2007). Besides, the insect-based protein is rich in lysine, threonine and methionine which is higher than those cereal- and legume-based protein (Spranghers et al. 2017; van Huis 2013). In the meantime, insects are good sources of lipid with high nutritional quality. The fatty acid composition of insects depends on several factors including species, feed composition, developmental stage, geographical locations, and extraction techniques (Tang et al. 2019; Tzompa-Sosa and Fogliano 2017). Previous research studies also revealed that insect-based lipids are rich in bioactive compounds such as tocols, sterols and carotenoids (Caligiani et al. 2019; Jeon et al. 2016; Kotake-Nara et al. 2002; Liland et al. 2017). These bioactive molecules are proven to provide several preventive and therapeutic health benefits. The commonly consumed insects include the orders Coleoptera (31%),

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Lepidoptera (18%), Hymenoptera (14%), Orthoptera (13%), Hemiptera (10%) and Diptera (2%), respectively (Kinyuru et al. 2015; van Huis 2013). The ultimate goal of this review is to provide a comprehensive information concerning the nutritional values of the fats and oils derived from insects of different orders. In this case, mealworm and red palm weevil larvae are selected to represent Coleoptera order. Silkworm pupae is chosen to be the representative for Lepidoptera order. Honeybee larvae, pupae and adult will be from Hymenoptera order. Locust and melon bug are elected for Orthoptera and Hemiptera, respectively. Lastly, black soldier fly larvae will be the choice for Diptera order. Besides, factors affecting the nutritional quality of the insect-based oils will also be discussed. The fatty acid composition and bioactive compounds in edible oil play an important role in determining its nutritional value and suitability to be used in various food systems. As one of the important food ingredients, the physicochemical properties of oil also affect the quality and consumer acceptability of the final food product. Therefore, this review will compile the information to provide knowledge or support on the future applications of insect-based oils in various food systems (Figure 1).

Coleoptera

Mealworm oil

Mealworm is the larval form of darkling beetle (*Tenebrio molitor*), an insect belongs to the order of Coleoptera and family of Tenebrionidae. Other common species includes giant mealworm (*Zophobas morio*) and lesser mealworm (*Alphitobius diaperinus*) (Selaledi, Mbajiorgu, and Mabelebele 2020). Mealworms inhabits temperate areas and probably originated from the Mediterranean region. They can feast on grains, vegetation and other fresh or spoiled food. A mealworm beetle experiences 4 distinct life stages (egg, larva, pupa and adult) and the entire life cycle takes about 4 – 12 months, depending on the environmental temperature and food availability (Ribeiro, Abelho, and Costa 2018). Mealworms are generally used as feed supplement for livestock owing to their high nutritional content, especially protein (45–70%) and fat (30–40%) (Finke 2005, 2015; Zhao et al. 2016). Recently, the edible oil derived from mealworm has attracted broad attention due to the comparable physicochemical properties with other vegetable oils (Son et al. 2020). More importantly, mass rearing of mealworm is effective and has low environmental impact, attributed to high feed conversion ratio, minimal physical space, water and energy input required. Therefore, mealworm oil (MO) can sometimes be regarded as an alternative option to palm oil, offering a viable solution to massive palm oil deforestation issue (Liu et al. 2020).

Fatty acid profile of mealworm oil

MO comprises mostly of unsaturated fatty acids with both oleic acid and linoleic acid contribute to almost 65% of the total fatty acid profiles (Table 1). The observation is uncommon because animal-based fats usually show a much lower unsaturated fatty acids (Nizar, Marikkar, and Hashim 2013). In addition, MO has high ω-6/ω-3 fatty acids ratio which is a pronounced characteristic of

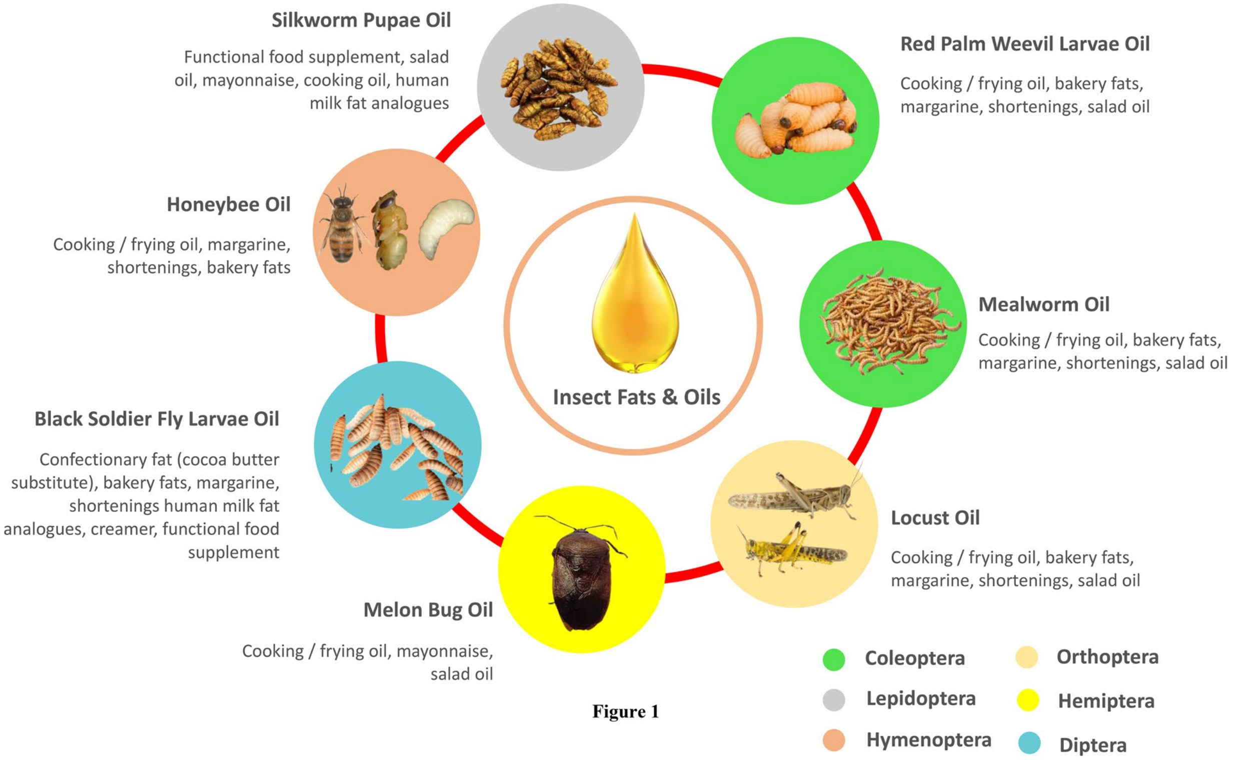

Figure 1. Applications of insect-based oils and fats in various food systems.

Table 1. Fatty acid composition of mealworm oil, red palm weevil larvae oil and silkworm pupal oil.

	Mealworm Oil	Red Palm Weevil Larvae Oil	Silkworm Pupal Oil
Characteristics	Range	Range	Range
Oil yield (% DW)	28.5 – 40.5	35.2 – 60.1	18.0 – 32.2
Fatty acid Composition, %			
C-6:0 Caproic	n.d.	0.1 – 0.2	n.d.
C-8:0 Caprylic	0.1	0.1	n.d.
C-10:0 Capric	n.d.	0.1 – 0.3	n.d.
C-12:0 Lauric	0.1 – 0.6	0.1 – 0.7	n.d.
C-14:0 Myristic	2.9 – 4.5	0.4 – 5.2	0.1 – 0.7
C-16:0 Palmitic	9.5 – 21.3	17.1 – 53.3	15.8 – 30.3
C-16:1 Palmitoleic	1.7 – 3.1	4.3 – 26.9	0.6 – 4.8
C-17:0 Heptadecanoic	n.d.	0.1 – 0.5	0.2 – 0.6
C-18:0 Stearic	1.6 – 8.0	0.1 – 7.8	2.0 – 7.1
C-18:1 Oleic	35.5 – 53.1	20.7 – 50.0	9.1 – 39.4
C-18:2 Linoleic	10.6 – 29.2	0.8 – 23.7	3.7 – 7.3
C-18:3 Linolenic	0.2 – 1.4	0.4 – 29.4	28.0 – 60.4
C-20:0 Arachidic	0.1 – 0.9	0.1 – 0.2	0.2 – 0.7
C-20:1 Gadoleic	0.1	n.d. – 0.2	n.d.
C-20:3 Eicosatrienoic	n.d.	n.d	0.2
C-20:5 Eicosapentaenoic	0.3 – 0.4	0.1 – 0.6	n.d.
C-20:4 Arachidonic	0.4 – 0.5	n.d. – 1.6	n.d.
C-22:4 Docosatetraenoic	0.5 – 0.6	n.d.	n.d.
Total SFA	21.5 – 36.5	27.2 – 55.4	28.2 – 28.8
Total USFA	63.5 – 78.5	44.5 – 72.9	71.3 – 71.6
Total ω-3	0.3 – 0.9	1.2 – 29.5	28.0 – 60.4
Total ω-6	12.7 – 28.7	3.16 – 24.2	3.7 – 7.3
Total MUFA	44.6 – 52.5	25.6 – 60.1	27.7 – 35.7
Total PUFA	18.9 – 26.0	4.3 – 46.4	41.6 – 43.6
Ratio ω-6 / ω-3	24.4 – 51.6	0.6 – 12.4	0.1 – 0.3

* Data are reported based on the previous studies; n.d. = not detected. Adapted from Heidari-Parsa et al. (2018), Jeon et al. (2016), Morales-Ramos et al. (2016), Otero et al. (2020), Paul et al. (2017), Purschke et al. (2017), Sipponen et al. (2018), Son et al. (2020), Tzompa-Sosa and Fogliano (2017), Tzompa-Sosa et al. (2019), Uğur (2019), Ugur et al. (2021), Chinarak, Chaijan, and Panpipat (2020), Chinarak et al. (2021), Cito et al. (2017), Emodi (2014), Hu et al. (2017), Kotake-Nara et al. (2002), Pan et al. (2012), Shanker et al. (2006), Tomotake, Katagiri, and Yamato (2010), Wei et al. (2009), Yu et al. (2018).

vegetable oils (Son et al. 2020). It is worth noting that MO contains about 22% of polyunsaturated fatty acids (PUFAs). However, the quality of the MO varies, depending the parameters such as feed composition, rearing condition, phenological and physiological parameters (pupal sex, development stage and generation) (Dreassi et al. 2017; Francardi et al. 2017; Morales-Ramos et al. 2016; van Broekhoven et al. 2015). For instance, Francardi et al. (2017) observed a significant increase in linolenic acid for MO when diet enriched with linseed oil was introduced, indicating a strong connection between the fatty acid profile of MO with the feeding diets. Another study also revealed that a feeding diet high in ω-6/ω-3 ratio increased the ω-6/ω-3 ratio in MO (van Broekhoven et al. 2015). At present, information regarding the nutritional value of pupal oil is limited. However, Morales-Ramos et al. (2016) reported that pupal oil contains higher oleic and stearic acids despite having similar fat content compared to MO.

The recent advances in the lipid extraction techniques could also enhance the nutritional properties of MO. For example, Sipponen et al. (2018) demonstrated that the supercritical CO_2 extraction method successfully improved the degree of unsaturation of MO by 15%. Another study also showed that the MO extracted by the ultrasound assisted method showed a higher linoleic acid content as compared to conventional solvent extraction approach (Otero et al. 2020). Similarly, Ugur et al. (2021) reported that high hydrostatic pressure-assisted extraction approach led to higher PUFAs, particularly arachidonic and eicosapentaenoic acids in MO.

Minor constituents of mealworm oil

MO contains considerable amount of tocols with γ-tocopherol being the major isomeric form, contributing to approximately 90% of the total tocopherols (Table 2). Several studies have demonstrated the potent health benefits of γ-tocopherol owing to its phenolic hydrogen group. It protects the human cells against radical-mediated damage, suppresses the intracellular reactive oxygen formation and cyclooxygenase activity (Zheng et al. 2020). The total phenolic content of MO is only 10 – 20% to that in olive oil and grape seed oil (Son et al. 2020). To increase the total phenolic content in MO, Ugur et al. (2021) reported that high pressure-assisted extraction method could disrupt the cell wall and increase the extractability of the antioxidative compounds from mealworm larvae.

Physicochemical properties of mealworm oil

MO has moderate oxidative stability with induction period of 36.0 h at 98 °C (Table 2). The shelf life of MO is estimated to be approximately 10 months at 20 °C based on the forecast model (Son et al. 2020). Even so, preliminary step such as roasting of mealworm at 200 °C for about 5 to 15 min could enhance the oxidative stability of MO (Jeon et al. 2016). The authors suggested roasting deactivates the deteriorative enzymes and leads to the formation Maillard reaction products with antioxidative properties in mealworm. Thus, MO can potentially be used to replace conventional vegetable oil as cooking or deep-frying oil owing to its high oxidative stability.

Table 2. Physicochemical properties of mealworm oil, red palm weevil larvae oil and silkworm pupal oil.

	Mealworm Oil	Red Palm Weevil Larvae Oil	Silkworm Pupal Oil
Characteristics	Range	Range	Range
Specific gravity (15°C)	0.85 – 0.89	0.80	0.91 – 0.93
Iodine value (g I_2/100 g oil)	72.5 – 91.6	41.7	119 – 124
Saponification number (mg KOH/g oil)	224.0 – 227.6	191.6	105 – 140
Oxidative stability index (110°C) (h)	n.r.	n.r.	26.7 – 64.6
Refractive index (25°C)	n.r.	n.r.	1.44 – 1.47
Cholesterol, %	0.1 – 0.6	74.6 – 2270.0	n.r.
Oxidative stability index (98°C) (h)	35.3 – 36.7	n.r.	n.r.
Viscosity (cP)	235 – 330	n.r.	n.r.
Tocols compounds (mg/kg oil)			
α-Tocopherol	6.2 – 6.4	14.2 – 26.2	73.3 – 131.0
β-Tocopherol	7.9 – 9.1	n.r.	8.5 – 15.0
γ-Tocopherol	120.8 – 126.2	n.r.	23.1 – 42.1
σ-Tocopherol	5.8 – 6.4	n.r.	20.3 – 36.0
Carotenoid (mg/kg oil)	n.r.	7.0 – 9.0	Carotenoid compounds (mg/kg oil) ** Neoxanthin – 12.8 Violaxanthin – 4.6 Lutein – 74.2
Sterol compounds (mg/kg oil)			
Cholesterol	n.r.	n.r.	586.3 – 895.6
Campesterol	n.r.	n.r.	47.0 – 68.6
Stigmasterol	n.r.	n.r.	43.0 – 47.6
β-sitosterol	n.r.	n.r.	240.0 – 366.0
Squalene (mg/kg oil)	16.1 – 26.1	n.r.	
Total polyphenol (mg GAE/g oil)	3.7 – 19.3	n.r.	42.0 – 79.6
Color	L (lightness): 38.9 a (redness): −1.9 b (yellowness): 7.5	Yellow	n.r.

* Data are reported based on the previous studies; **Carotenoid profile is calculated based on the assumption that carotenoid compounds are concentrated in the lipid fraction of silkworm pupae; n.r. = not reported. Adapted from Chinarak, Chaijan, and Panpipat (2020), Chinarak et al. (2021), Cito et al. (2017), Emodi (2014), Heidari-Parsa et al. (2018), Hu et al. (2017), Jeon et al. (2016), Kotake-Nara et al. (2002), Morales-Ramos et al. (2016), Otero et al. (2020), Pan et al. (2012), Paul et al. (2017), Purschke et al. (2017), Shanker et al. (2006), Sipponen et al. (2018), Son et al. (2020), Tomotake, Katagiri, and Yamato (2010), Tzompa-Sosa and Fogliano (2017), Tzompa-Sosa et al. (2014), Tzompa-Sosa et al. (2019), Ugur et al. (2021), Wei et al. (2009), Zhao et al. (2016).

An analysis on the acylglycerol profile shows that MO has high concentrations of triacylglycerol (TAG) with Equivalent Carbon Number (ECN) 50–54. The acylglycerol pattern of MO differs from most vegetable oils and animal fats with ECN 44–48 and ECN 48–50, respectively (Tzompa-Sosa et al. 2014). Due to the large differences in the fatty acid composition within the TAG molecules, MO exhibits four distinct crystallization peaks ($P_{cry,1}$ = 45.4 °C, $P_{cry,2}$ = −19.9 °C, $P_{cry,3}$ = −5 °C and $P_{cry,4}$ = 3.6 °C) and three melting peaks ($P_{melt,1}$ = −24.7 °C, $P_{melt,2}$ = −17.4 °C and $P_{melt,3}$ = 16.7 °C) in the differential scanning calorimetry (DSC) thermograms (Tzompa-Sosa, Verbeek and Van Valenberg 2016). A detailed investigation of the crystallization and melting peaks reveals a large separation by the temperature region of 5 – 10 °C, indicating that the solid and the liquid parts coexist at certain temperature (Tzompa-Sosa and Fogliano 2017; Tzompa-Sosa et al. 2019). Therefore, MO can be separated into both olein and stearin fractions using either dry or wet fractionation technique. Tzompa-Sosa and Fogliano (2017) successfully fractionated the two fractions at crystallization temperature of 2 °C and 4 °C for 24 h. The olein fraction showed two crystallization peaks at temperature much lower than −5 °C and its last melting peak reduced from 16.7 °C to up to 3.2 °C. On the other hand, the stearin fraction lacked the crystallization point at −5 °C and showed an increase in the highest crystallization point up to 10.7 °C. The melting point of the solid fraction increased from 16.7 °C to more than 21 °C (Tzompa-Sosa and Fogliano 2017). The MO stearin fraction can act as a suitable fat hard stock in margarine formulation.

The antibacterial effect of MO against some pathogenic bacteria including *Pasteurella multocida* and *Yersinia enterocolitica* has also been reported (Dabbou et al. 2020). Therefore, MO could possibly act as a natural preservative in different food systems. With the desired physicochemical characteristics and high nutritional values, MO demonstrates great potential in various food applications.

Red palm weevil larval oil

Red palm weevil, scientifically known as *Rhynchophorus ferrugineus*, has the common name of sago palm weevil or Asian palm weevil. It belongs to the Coleoptera order and the Curculionidae family. A complete life cycle of red palm weevils comprises egg, larva, pupa, and adult. The larval, pupal, and adult stages of red palm weevil vary between one to ten months, two to three weeks, and one to three months, respectively, whose values are subjected to changes by temperature (Rochat et al. 2017). Being originated from southern Asia and Melanesia, red palm weevil displayed strong ability in adapting different climatic and ecological conditions after it has spread rapidly to the Middle East, Europe, North Africa, Latin America, and other regions (Peri et al. 2017; Rugman-Jones et al. 2013; Sabit et al. 2021). It is one of the insect pests that attacks several palm species such as sago, coconut, betel, oil palm, and date palm, resulting in economic losses. Therefore, research attentions have always been focusing on monitoring and controlling red palm weevil infestation (Abdelsalam et al. 2021; Yan et al. 2021). Nonetheless, red palm weevil larvae (RPWL) are among the popular edible insects in southern Thailand. RPWL are rich in lipid, whose value ranges from 35.2 to 60.1% (Chinarak, Chaijan, and Panpipat 2020; Chinarak et al. 2021; Cito et al. 2017). With such considerable amount of lipid content, ease of rearing, and short period before harvesting, RPWL show a potential source of edible insect oil.

Fatty acid profile of red palm weevil larval oil

The three most abundant fatty acids in RPWL oil are oleic (20.7 – 50.0%), palmitic (17.1 – 53.3%), and palmitoleic (4.3 – 26.9%) acids, as shown in Table 1. Other major fatty acids in RPWL oil includes myristic, stearic, linoleic, and linolenic acids even if the data reported in the literature show high degree of variability. Similar to palm olein, most of the available studies reported a balanced profile of saturated and unsaturated fatty acids in RPWL oil whose compositions range from 40 to 60% (Chinarak, Chaijan, and Panpipat 2020; Cito et al. 2017; Emodi 2014). However, a recent study by Chinarak et al. (2021) found RPWL oil to contain predominantly unsaturated fatty acids (65.7 – 72.9%). The reason behind this difference in fatty acid profile remains unclear regardless of the similarity in rearing techniques and feed composition used by the same group of researchers (Chinarak, Chaijan, and Panpipat 2020; Chinarak et al. 2021). Likewise, a wide range of ω-6/ω-3 ratio (0.6 – 12.4) was also reported.

No major difference was found in the fatty acid profile of the oil extracted from RPWL raised by different farms in Thailand, despite some minor variations in rearing technique and feed composition which consisted mainly of ground sago palm trunk with distinct degree of supplementation with rice bran, molasses, effective microorganisms, and pig feed (Chinarak, Chaijan, and Panpipat 2020). This is in agreement with the findings of Cito et al. (2017) who found similar fatty acid composition in the oils of laboratory-raised apple-fed RPWL and those wild RPWL collected from infested *Syagrus romanzoffiana* and *Phoenix canariensis* palm trees. In contrast, Chinarak et al. (2021) found that the ω-3 and ω-6 contents of RPWL oil are affected by their respective amounts in the feed. The most noticeable modifying effect was observed in the perilla seed-supplemented diet of ground sago palm trunk which raised the essential α-linolenic and linoleic acids contents by 26.25 and 5.37 times, respectively. This greatly reduced the ω-6/ω-3 ratio from 2.7 to 0.6. Supplementation with pig feed, rice bran, and corn meal raised the linoleic acid content of RPWL oil to a greater extent than α-linolenic acid, which raised the ω-6/ω-3 ratio to as high as 12.4.

To the best of the authors' knowledge, no study on the effect of different extraction techniques on the fatty acid profile of RPWL oil has been conducted previously. In fact, limited research attentions have been allocated to the characterization of RPWL oil and hence, further investigation may be required for a better understanding of RPWL oil.

Minor constituents and physicochemical properties of red palm weevil larval oil

Studies reporting the physicochemical properties of RPWL oil are scarce. The physicochemical properties and minor constituents of RPWL oil are presented in Table 2. RPWL oil has a yellow color due to its carotenoid content. The amounts of total tocopherol and carotenoid in RPWL oil were reported to increase when higher proportion of pig feed, which contains soybean meal and corn meal as the source of carotenoid, was incorporated into the basic diet of sago palm trunk (Chinarak, Chaijan, and Panpipat 2020). However, the proportion of each type of tocopherol was not illustrated previously. A large range of cholesterol content was also reported by researchers from Thailand (Chinarak, Chaijan, and Panpipat 2020) and Italy (Cito et al. 2017). There are still knowledge gaps on the physicochemical properties of RPWL oil available for further scientific research to aid the use of RPWL oil in various food systems in the future. Nevertheless, one can assume that RPWL oil can be utilized in some food applications including cooking oil, bakery fats, margarine, shortenings and so on based on its fatty acid profile.

Lepidoptera

Silkworm pupal oil

Silkworms are the producers of silk fabrics. There are several domesticated silkworm species including Mulberry silkworms (*Bombyx mori*), oak silkworm (*Antheraea pernyi*) and the eri silkworm (*Samia cynthia ricini*). The former is the insect species that receives much attention recently (Zhou and Han 2006). Silk is harvested from the silkworms when they enter the pupal phase of their lifecycle and create cocoons protecting themselves. These silkworm pupae are the major by-products generated after silk farming (Altomare et al. 2020; Hu et al. 2017). The pupae have high amounts of proteins, fats, minerals and vitamins. Therefore, they are frequently used as animal feed or fertilizer (Altomare et al. 2020). The consumption of silkworm pupae has been long practised in Asia countries including China, India, Japan and Korea (Zhou and Han 2006). In China, silkworm pupae are used as Chinese medicine to treat hypertension and fatty liver (Wu et al. 2021). Previous studies indicated that silkworm protein and hydrolyzed peptide exhibited physiological functions including enhancing immunity response, antitumor, antihypertensive, antimicrobial, anti-inflammatory and antioxidative activity (Altomare et al. 2020; Wu et al. 2021). Consequently, silkworm pupae are the research subject of study in recent years.

Fatty acid profile of silkworm pupal oil

As tabulated in Table 1, dry silkworm pupae contain about 25% of fat content, depending on the extraction methods. For instance, cold maceration method using petroleum ether solvent could only extract < 7% silkworm pupal oil (SWPO) while the Soxhlet extraction method showed a higher extraction yield of 29% (Winitchai, Manosroi, and Manosroi 2008). Interestingly, SWPO comprises mostly unsaturated fatty acids, accounting to 70 – 80% of the total fatty acid composition. Its exceptionally high ω-3 fatty acid content, particularly α-linolenic acid (~50%) and low ω-6/ω-3 ratio (0.1 – 0.3) make SWPO an excellent source of edible oil as high intake of oil with these characteristics has been linked to the suppression of cardiovascular disease, cancer, and inflammatory and autoimmune diseases (Simopoulos 2008). The ω-6/ω-3 ratio in SWPO is even comparable to some functional seed oils such as chia seed oil and flaxseed oil (Ciftci, Przybylski, and Rudzińska 2012; Kulczyński et al. 2019; Nitrayová et al. 2014). In a rat study, Mentang et al. (2011) also reported the suppressive effect of SWPO on the formation of arachidonic acid in the liver and red blood cell membrane, thereby reducing the formation of ω-6 PUFA-derived eicosanoids that are responsible for several inflammatory disorders. Their study also demonstrated that SWPO could lower the lipid synthesis, up-regulate fatty acid oxidation in the liver and reduce the glucose level and body fat accumulation in rats (Mentang et al. 2011). Another similar study also showed that rats fed with SWPO for 18 weeks exhibited a notable increase in high density lipoprotein cholesterol levels with cardiovascular protective effect (Longvah, Manghtya, and Qadri 2012).

The fatty acid profile of SWPO might vary according to the species origin, feeding diet, season and geographical regions. For example, the SWPO derived from eri silkworm reared on tapioca-based diet has pronounced α-linolenic acid content (~60%) as compared to castor-based diet (~45%) (Shanker et al. 2006). Similarly, Yu et al. (2018) found a positive relationship between the amount of C-20 (eicosapentaenoic acid) and C-22 (docosahexaenoic acid) PUFAs in SWPO with the degree of fish oil supplementation in the silkworm's diet. A 10% higher α-linolenic acid in mulberry SWPO relative to oak SWPO was also reported previously (Pan et al. 2012). Another study demonstrated that female pupae contain higher amount of PUFAs (linoleic and α-linolenic acids) compared to male pupae as female needs more energy for oviposition (Yu et al. 2018).

Minor constituents of silkworm pupal oil

The total tocopherol content in SWPO is generally high, ranging from 125 to 224 mg/kg, which is comparable to commercial vegetable oils including soybean oil (265 mg/kg) and linseed oil (244.2 mg/kg) (Kotake-Nara et al. 2002). The main tocopherol species in SWPO is α-tocopherol, contributing > 50% of the total tocopherol content. It is also worth-mentioning that a significant level of carotenoids such as lutein, neoxanthin and violaxanthin was detected in silkworm pupae. Although the authors did not analyze the carotenoid content in SWPO, one can assume that these bioactive compounds will be extracted together with the insect oil due to the lipophilic nature of these biomolecules. Besides, a previous study reported that SWPO showed a high total phenolic content (42.0 – 79.6 mg GAE/kg oil), thereby exhibiting a strong antioxidant activity (Hu et al. 2017). In addition, some sterol compounds are also spotted in SWPO with cholesterol being the primary sterol species, followed by β-sitosterol, campesterol and stigmasterol (Table 2) (Shanker et al. 2006).

Physicochemical properties of silkworm pupal oil

Kotake-Nara et al. (2002) observed that SWPO showed a low consumption of oxygen after being incubated at 50 °C for 800 h, whereas a huge drop in oxygen level was detected for both linseed oil and soybean oil after 180 h and 300 h of incubation. Although SWPO has a high degree of unsaturation (> 60%), its high concentrations of tocopherols, carotenoids and sterols compounds grant it an excellent oxidative stability.

Approximately 40% of the total TAGs in SWPO has an ECN 40 which is attributed to LLLn, LnLnP or LnLnO. TAGs species with ECN 44 (LnOO, OLL, SLLn, PLL, or PLnP) is the second largest TAG group that contributes to about 23% of the total TAG content. Shanker et al. (2006) noticed that the *sn*-2 position of most TAG species in SWPO is esterified predominantly by unsaturated fatty acids such as linoleic and linolenic acid. The presence of unsaturated fatty acids at *sn*-2 position appears to enhance the bioavailability of these fatty acids because they are directly absorbed by the intestine. Therefore, it enables the biosynthesis of their higher homologues such as arachidonic, eicosapentaenoic and docosahexaenoic acids and their subsequent conversion to eicosanoids (Shanker et al. 2006). Therefore, SWPO can be used to produce human milk fat analogue enriched with α-linolenic acid. In addition, SWPO can serve as nutritive and dietary supplement.

Hymenoptera

Honeybee-based oil

Honeybee is the collective name for the genus *Apis* under the class Insecta, order Hymenoptera, and family *Apidae*. There are ten generally recognized species under the genus *Apis*. Out of them, the western honeybee or European honeybee, *Apis mellifera*, is the most widely spread species across the world due to the work of beekeepers whereas the other species are still limited in Asia only (Han, Wallberg, and Webster 2012). *A. mellifera* received the most scientific attention and was called the champion honey producer due to its ability to adapt to the temperate region by storing a large amount of honey in nest for overwintering (Breed 2019).

There are three types of bees, namely queen, drone, and worker. Drones, the male bees, develop from unfertilized eggs and are responsible to mate with the queen. Fertilized eggs will develop into workers or queen if fed with honey or royal jelly, respectively. All of them undergo development from eggs, larvae, pupae to adults with different duration. Only one queen is usually present in a bee nest. The number of drones ranges from 0 to 200 and most of the bees are workers (20,000 to 200,000) (Devillers 2003). Bees has been reported as edible insect in China, Mexico, and Thailand (Chen et al. 1998; Chen, Feng, and Chen 2009; Ramos-Elorduy et al. 1997). Due to the prevalence of workers in the bee nest, consuming workers is the most sustainable as compared to the other bee types.

Fatty acid profile of worker bee larvae oil

A good oil yield ranging from 14.5 to 32.2% was reported from the larvae of honeybee worker (Bednářová et al. 2013; Haber et al. 2019; Ramos-Elorduy et al. 1997). As shown in Table 3, worker bee larvae oil (WBLO) is predominantly composed of long chain fatty acids with the absence of short chain fatty acids. The major fatty acids are palmitic (37.3 – 42.2%), oleic (20.4 – 47.5%), stearic (10.4 – 12.3%), and myristic (2.4 – 11.5%) acids, which make up of 79.0 – 99.0% of the total fatty acids present. The data also indicates that saturated fatty acids (50.0 – 62.3%) present at a higher percentage than those of unsaturated (37.8 – 50.0%). Oleic acid is the dominant unsaturated fatty acids (24.8 – 48.2%) whereas PUFAs present at a relatively low amount (n.d. – 13.0%). Notably, the WBLO lacks the essential ω-3 and ω-6 fatty acids with values typically ranging from not detected to 2.6% (Ghosh, Jung, and Meyer-Rochow 2016; Haber et al. 2019; Robinson and Nation 1970). Higher amounts of ω-3 and ω-6 fatty acids at 4.5% and 8.5%, respectively, were reported in oil extracted from the mixture of larvae and pupae by Bednářová et al. (2013).

Fatty acid profile of worker bee pupal oil

The pupae of honeybee worker are also rich in oil with a reported yield of 16.0 – 31.24% (Bednářová et al. 2013; Finke 2005; Ghosh, Jung, and Meyer-Rochow 2016; Haber et al. 2019; Ramos-Elorduy et al. 1997). As shown in Table 3, a similar fatty acid profile to the larvae with the principal fatty acids of palmitic (28.7 – 36.8%), oleic (20.4 – 48.7%), stearic (10.4 – 14.4%), and myristic (2.4 – 11.5%) acids is found in the worker bee pupal oil (WBPO). These fatty acids make up of 79.0 – 98.2% of the total fatty acids. Saturated fatty acids (47.6 – 62.3%) are also generally present at a higher percentage than the unsaturated fatty acids (37.8 – 52.4%) which are mostly monounsaturated (24.8 – 48.9%) rather than polyunsaturated (n.d. – 13.0%). Similar to the larvae, ω-3 and ω-6 fatty acids were reported as minor in the pupae with values typically ranging from not detected to 2.3% (Finke 2005; Ghosh, Jung, and Meyer-Rochow 2016; Haber et al. 2019; Robinson and Nation 1970).

Fatty acid profile of worker bee adult oil

The adults of honeybee worker are less fatty with a reported oil yield of 6.9% (Table 3) (Ghosh, Jung, and Meyer-Rochow 2016). Oleic acid (45.2 – 61.8%) is the most abundant fatty acids in adults, followed by palmitic (7.0 – 17.9%) and stearic (7.0 – 13.7%) acids. The amount of myristic acid (0.6 – 1.4%) is lesser compared to the immature stages. In contrast to the immature stages, the adults contain more unsaturated fatty acids (69.1 – 77.5%) than the saturated fatty acids (15.4 – 34.1%). This unsaturation is dominated by the monounsaturated fatty acids (MUFAs) (61.8 – 67.0%) instead of the PUFAs (7.3 – 14.3%). As illustrated in the works of Ghosh, Jung, and Meyer-Rochow (2016) and Robinson and Nation (1970), from the developmental stage of larvae to adults, the amount of total saturated fatty acids, contributed particularly by palmitic acid, decreases substantially. This was complemented with the increases in the amounts of oleic, linoleic, α-linolenic, and eicosenoic acids, thereby giving rise to an overall unsaturated fatty acids-rich lipid profile.

Table 3. Fatty acid composition of honeybee larval oil, honeybee pupal oil and honeybee adult oil.

	Honeybee Larval Oil	Honeybee Pupal Oil	Honeybee Adult Oil
Characteristics	Range	Range	Range
Oil yield (% DW)	14.5 – 31.2	16.0 – 31.24	6.9
Fatty acid Composition, %			
C-10:0 Capric	n.d.	n.d.	0.2
C-12:0 Lauric	0.1 – 0.8	0.1 – 0.5	0.3 – 0.8
C-14:0 Myristic	2.4 – 11.5	2.4 – 11.5	0.6 – 1.4
C-16:0 Palmitic	37.3 – 42.2	28.7 – 36.8	7.0 – 17.9
C-16:1 Palmitoleic	trace – 4.4	n.d. – 4.4	trace – 2.6
C-17:0 Heptadecanoic	n.d.	n.d.	n.d. – 0.4
C-18:0 Stearic	10.4 – 12.3	10.8 – 14.4	7.0 – 13.7
C-18:1 Oleic	20.4 – 47.5	20.4 – 48.7	45.2 – 61.8
C-18:2 Linoleic	n.d. – 8.5	n.d. – 8.5	trace – 7.8
C-18:3 Linolenic	n.d. – 4.5	n.d. – 4.5	n.d. – 7.3
C-20:0 Arachidic	n.d. – 3.6	n.d. – 3.6	n.d.
C-20:1 Eicosenoic	n.d.	n.d. – 0.8	n.d. – 19.2
C-22:0 Behenic	n.d. – 1.0	n.d. – 2.1	n.d. – 0.4
Total SFA	50.0 – 62.3	47.6 – 62.3	15.4 – 34.1
Total USFA	37.8 – 50.0	37.8 – 52.4	69.1 – 77.5
Total ω-3	n.d. – 4.5	n.d. – 4.5	n.d. – 7.3
Total ω-6	n.d. – 8.5	n.d. – 8.5	trace – 7.8
Total MUFA	24.8 – 48.2	24.8 – 48.9	61.8 – 67.0
Total PUFA	n.d. – 13.0	n.d. – 13.0	7.3 – 14.3
Ratio ω-6 / ω-3	0 – 1.9	0 – 1.9	0 – 1.1

* Data are reported based on the previous studies; n.d. = not detected. Adapted from Bednářová et al. (2013), Finke (2005), Ghosh, Jung, and Meyer-Rochow (2016), Haber et al. (2019), Ramos-Elorduy et al. (1997), Robinson and Nation (1970).

Although a natural diet composed of pollen and nectar was found to favor a higher mineral and polyphenolic contents in the bees, supplementation of diet with sucrose solution was found to have no substantial effect on the fatty acid profile of *A mellifera* worker larvae and pupae (Haber et al. 2019). This is in agreement with an earlier finding by Robinson and Nation (1970) who found no close correlation between the fatty acid profile of the pollen and that of the *A. mellifera* in larvae, pupae, and adult stages.

Orthoptera

Locust oil

The two major locust species that receive much research attention are desert locust (*Schistocerca gregaria*) and migratory locust (*Locusta migratoria*) owing to their high fecundity and high acceptability by animals as feed. They belong to the order of Orthoptera and family of Acrididae. The desert locust is commonly detected in Africa, the Middle East and Asia whereas the migratory locust is the species with wide global distribution (Mariod, Saeed-Mirghani, and Hussein 2017). A locust swarm is a great source of biomass, containing approximately 10 billion insects and weighing up to 30,000 tonnes. Therefore, locusts can be an important food source. In African and Asian countries, locust is considered as delicacy and widely consumed (Kinyuru 2021; Kinyuru and Ndung'u 2020; van Huis 2013).

Fatty acid profile of locust oil

Table 4 shows the fatty acid profile of locust oil (LO). The locusts appear to contain high fat content (~30%) which is higher than the average of orthopteran species (~14%) (Rumpold and Schlüter 2013). However, the amount of lipid derived from locusts is dependent on several parameters including feeding diet, geographical location and species. For instance, Oonincx and van der Poel (2011) reported that the diet enriched with wheat bran could increase the fat content of locusts by almost 25%. Also, Osimani et al. (2017) obtained a lower percentage of fat in migratory locust sourced from Netherlands.

LO is high in unsaturated fatty acids such as oleic acid (34%), linoleic acid (17%) and α-linolenic acid (11%) (Mohamed 2015; Ramos-Bueno et al. 2016; Zielińska et al. 2015). Previous study indicated that the fatty acid profile of LO is correlated with the geographical origin (Osimani et al. 2017). The researchers indicated that the locusts from Netherlands showed a lower unsaturated fatty acid content. LO can be considered as healthy oil because of its moderately high amount of α-linolenic acid. Besides, the ω-6/ω-3 fatty acid ratio is around 1.5 which is lower than the maximum threshold level of 10:1 (FAO 2010; Simopoulos 2002, 2004). In addition, LO has a balanced fatty acid profile with the ratio of PUFA to saturated fatty acid of 0.7 which is close to the ideal value of 1. Therefore, LO can be counted as a potential healthy lipid source.

Table 4. Fatty acid composition of locust oil, melon bug oil and black soldier fly larvae oil.

	Locust oil	Melon bug oil	Black soldier fly larvae oil
Characteristics	Range	Range	Range
Oil yield (% DW)	18.9 – 38.3	45.0 – 55.0	11.2 – 46.7
Fatty acid Composition, %			
C-6:0 Caproic	0.4	n.d.	n.d.
C-10:0 Capric	0.1	n.d.	0.8 – 3.1
C-12:0 Lauric	0.1 – 1.0	n.d.	28.8 – 60.9
C-14:0 Myristic	1.6 – 3.6	0.3 – 0.4	3.9 – 11.5
C-16:0 Palmitic	22.6 – 37.7	30.5 – 31.6	8.2 – 21.9
C-16:1 Palmitoleic	1.0 – 1.9	10.4 – 10.9	2.3 – 8.0
C-17:0 Heptadecanoic	0.2 – 0.6	2.3 – 2.5	n.d.
C-18:0 Stearic	2.4 – 10.0	3.2 – 3.8	1.5 – 5.3
C-18:1 Oleic	30.4 – 38.0	45.2 – 47.4	9.5 – 23.4
C-18:2 Linoleic	8.4 – 24.9	3.6 – 4.9	1.4 – 13.0
C-18:3 Linolenic	3.0 – 18.3	0.1 – 0.5	0.1 – 3.6
C-20:0 Arachidic	0.4 – 0.5	0.2 – 0.3	0.1
C-20:0 Behenic	0.1	n.d.	n.d.
C-20:1 Gadoleic	n.d.	0.2	n.d.
C-20:3 Eicosatrienoic	0.3	n.d.	n.d.
C-20:4 Arachidonic	n.d.	n.d.	0.1 – 1.3
C-20:5 Eicosapentaenoic	n.d.	n.d.	0.1
C-22:6 Docosahexaenoic	0.1	n.d.	n.d.
Total SFA	33.6 – 41.0	37.3 – 38.5	45.3 – 82.8
Total USFA	59.0 – 66.5	60.3 – 62.7	15.1 – 35.2
Total ω-3	11.3 – 12.1	0.4 – 0.5	0.9 – 2.3
Total ω-6	5.6 – 14.6	3.6 – 4.9	4.6 – 11.6
Total MUFA	31.7 – 41.2	56.4 – 57.5	9.5 – 19.1
Total PUFA	17.8 – 34.8	3.9 – 5.5	6.8 – 16.6
Ratio ω-6 / ω-3	0.6 – 2.4	7.2 – 12.3	2.0 – 12.9

* Data are reported based on the previous studies; n.d. = not detected. Adapted from Alnadif et al. (2007), Barragan-Fonseca, Dicke, and van Loon (2017), Caligiani et al. (2019), Ewald et al. (2020), Kinyuru (2021), Liland et al. (2017), Liu et al. (2017), Mai et al. (2019), Mariod (2011), Mariod (2013), Mariod et al. (2005), Mariod et al. (2006a), Mariod et al. (2008), Mariod, Abdel-Wahab, et al. (2011), Mariod, Mattaus and Eichner (2004), Mariod, Matthäus, and Abdel-Wahab (2011), Mariod, Matthäus, and Hussein (2011), Matthäus et al. (2019), Matthäus, Eichner and Hussein (2015), Mohamed (2015), Osimani et al. (2017), Ramos-Bueno et al. (2016), Spranghers et al. (2017), Zielińska et al. (2015).

Minor constituents and physicochemical properties of locust oil

Despite the tocol and carotenoid content in LO is not well explored, the locust meal is in fact high in α-tocopherol (267.5 µg/g) and carotenoid compounds including retinol (0.2 mg/kg), lutein (2.0 mg/kg) and β-carotene (5 mg/kg) (Table 5) (Oonincx and van der Poel 2011). These lipid soluble bioactive compounds will leach out together with the insect lipid during extraction. Previous study also revealed that LO showed substantial amount of sterol compounds. The presence of sterol compounds in insects is not common because most of them are not able to synthesize sterols *de novo* from the isoprenoid precursors (Blásquez, Moreno, and Camacho 2012; Jing, Grebenok, and Behmer 2013). These nutrients are acquired from the dietary sources. For example, a study reported that the dessert locust fed *ad libitum* on wheat seedlings showed high sterol content (Cheseto et al. 2015). More interestingly, the authors found five unique sterols compounds namely 7-dehydrocholesterol, desmosterol, fucosterol, (3β,5α) cholesta-,14,24-trien-3-ol,4,4-dimethyl and (3β,20 R) cholesta-5,24-dien-3,20-ol which are not detected in the feeding diet. The study suggested that desert locust could

Table 5. Physicochemical properties of locust oil, melon bug oil and black soldier fly larvae oil.

	Locust oil	Melon bug oil	Black soldier fly larvae oil
Characteristics	Range	Range	Range
Oxidative stability index (120 °C) (h)	n.r.	36.5 – 46.0	49.2 – 52.0
Kinematic viscosity (40 °C) (mm^2/s)	n.r.	34.9 – 35.1	n.r.
Viscosity (cP)	n.r.	n.r.	96 – 101
Specific gravity (4°C)	0.93 – 0.94	n.r.	0.908 – 0.914
Iodine value (g I_2/100 g oil)	74.3 – 75.7	n.r.	19.3 – 75.6
Saponification number (mg KOH/g oil)	170 – 172	n.r.	213 – 252
Refractive index (25°C)	1.44 – 1.48	n.r.	n.r.
Tocols compounds (mg/kg oil) **	n.r.	n.r.	n.r.
α-Tocopherol	827	0.7 – 3.8	30.2 – 30.4
α-Tocotrienol	n.r.	n.d.	2.7
β-Tocopherol	n.r.	n.r.	9.6 – 9.8
β-Tocotrienol	n.r.	n.r.	19.7 – 19.9
γ-Tocopherol	n.r.	0.4 – 2.4	22.2
Carotenoid compounds (mg/kg oil) **		n.r.	n.r.
Retinol	0.2 – 1.7		
Lutein	1.3 – 3.0		
Zeaxanthin	0.1 – 0.3		
β-cryptoxanthin	0.2 – 0.5		
α-carotene	0.1		
cis-β-carotene	1.0 – 2.3		
trans-β-carotene	4.2 – 9.0		
Sterol compounds (mg/g oil) ***			
Cholesterol	1880.5	14.0 – 40.0	17.5 – 20.5
Brassicasterol	n.r.	n.r.	16.5 – 21.7
24-Methylencholesterol	n.r.	n.r.	15.9 – 18.1
7-Dehydrocholesterol	921.4	n.r.	n.r.
Lathosterol	n.d.	n.r.	n.r.
Desmosterol	232.3	n.r.	n.r.
Campesterol	n.r.	18.0 – 171.0	868.9 – 910.5
Campestanol	n.r.	n.r.	142.0 – 154.2
Stigmasterol	n.r.	8.0 – 40.0	67.5 – 72.7
7-Campesterol	n.r.	n.r.	46.9 – 50.5
5,23-Stigmastadienol	n.r.	n.r.	27.4 – 30.2
5,24-Stigmastadienol	n.r.	n.r.	23.5 – 23.7
Chlerosterol	n.r.	n.r.	8.9 – 11.1
(3β,5α) Cholesta-,14,24-trien-3-ol,4,4-dimethyl	102.9	n.r.	n.r.
Cholesterol, 7-oxo	1251.9	n.r.	n.r.
(3β,20R) Cholesta-5,24-dien-3,20-ol	59.0	n.r.	n.r.
β-sitosterol	436.6	106.0 – 696.0	1823.8 – 1908.2
Sitostanol	n.r.	n.r.	184.7 – 190.3
Fucosterol	235.2	n.r.	n.r.
Δ5-avenasterol	n.r.	5.0 – 25.0	120.2 – 124.0
Δ7-stigmastenol	n.r.	9.0 – 45.0	85.2 – 86.6
Δ7-avenasterol	n.r.	n.r.	5.4 – 39.0
Others^{+}	n.r.	175.0 – 1063.0	n.r.
Total polyphenol (mg GAE/g oil)	n.r.	206.3 – 206.9	6.9 – 20.1
Color	n.r.	n.r.	L (lightness): 65.24 C (chroma): 21.52 H (hue angle): 110.4

* Data are reported based on the previous studies; n.r. = not reported, **Tocopherol and Carotenoid profile is calculated based on the assumption that tocopherol and carotenoid compounds are concentrated in the lipid fraction of locust after extraction. *** Data are reported based on the fat body of locust. $^{+}$Others include 24-methylcholesterol, campestanol, chlerosterol, sitostanol and 5,24-stigmastadienol. Adapted from Alnadif et al. (2007), Barragan-Fonseca, Dicke, and van Loon (2017), Caligiani et al. (2019), Cheseto et al. (2015), Ewald et al. (2020), Kinyuru (2021), Liland et al. (2017), Liu et al. (2017), Mai et tal. (2019), Mariod (2011), Mariod (2013), Mariod et al. (2005), Mariod et al. (2006a), Mariod et al. (2008), Mariod, Mattaus and Eichner (2004), Mariod, Matthäus, and Abdel-Wahab (2011), Mariod, Matthäus, and Hussein (2011), Matthäus et al. (2019), Matthäus, Eichner and Hussein (2015), Oonincx and van der Poel (2011), Ramos-Bueno et al. (2016), Spranghers et al. (2017).

amplify the phytosterols derived from the feeding diet and metabolize them into different derivatives with potential health benefits such as chemo-preventive, anti-inflammatory, antioxidant and antidiabetic effects (Patel and Thompson 2006; Yoshida and Niki 2003). To date, the information on the physicochemical properties of LO remains vague and unexplored. Yet, LO could possibly be utilized for various food applications including cooking or frying oil, bakery fats, margarine, shortening and others, attributed to its balanced fatty acid composition and high bioactive compounds.

Hemiptera

Melon bug oil

The melon bug *Coridius viduatus* (formerly *Aspongopus Viduatus*) (Hemiptera: Dinidoridae) is one of the most devastating pests threatening watermelon. The adult nymphs pierce leaves, stems and young fruits, sucking the sap from the plants and causing wilting, fruit drop and death of the plants (Mariod, Matthaus, and Eichner 2004; Mariod 2020). The melon bugs are widely distributed in the Near East and Africa (Mariod 2020; Tarla, Yetisir, and Tarla 2013). The melon bug is rich in protein and fat content, contributing to 27.0% and 54.2% of the dry weight, respectively. The applications of melon bug oil (MBO) for cooking purpose and some medical treatments including skin lesion remedy in Sudan are well documented (Mariod 2020).

Fatty acid profile of melon bug oil

Melon bug is a good source of oil ranging from 44 to 55%. As shown in Table 4, MBO is composed mainly of MUFAs especially oleic acid and palmitoleic acid at a concentration of 46% and 10%, respectively. This characteristic is not common in most insect-based lipids. In addition, MBO is rich in palmitoleic acid (10.4 – 10.9%) as an important ω-7 fatty acid. The fatty acid profile of the MBO is comparable to palm oil in which the latter contains significant amount of palmitic acid and oleic acid in the ratio of ~ 1:1. These two fatty acids contribute up to 80% of the total fatty acid composition in palm oil (Mancini et al. 2015; Montoya et al. 2014). Hence, MBO is speculated to exhibit good oxidative stability at elevated temperature owing to its high saturated fatty acid and MUFA content (Cao et al. 2015).

Minor constituents of melon bug oil

As shown in Table 5, MBO appears to show high total phenolic compounds (206.3 – 206.9 mg/kg oil) as compared to some conventional oils such as groundnut oil, coconut oil, rice bran oil, mustard oil, sunflower oil and sesame oil with total phenolic content of 30.9, 18, 8.9, 5.6, 4.9, and 3.3 mg/kg, respectively (Janu et al. 2014; Matthäus et al. 2015). The phenolic and flavonoid compounds in MBO were identified to be *tans*-cinnamic acid and syringic acid, quercetin and pelargonin (Mariod et al. 2015). MBO is also a good source of sterol compounds with β-sitosterol being the main sterol species up to 696 mg/kg (Alnadif et al. 2007; Mariod et al. 2006a, 2006b). However, the extraction of these bioactive components largely depends on the choice of extraction solvents and methods. Mariod et al. (2006a) pointed out that the organic solvents could enhance the concentration of high-value bioactive molecules (tocopherols and sterols) in MBO.

Physicochemical properties of melon bug oil

The oxidative stability of the edible oil is well correlated with the bioactive components (tocols and sterols compositions), trace metals and fatty acid composition of oil (Mariod et al. 2006a, 2006b, 2008). Attributed to its high sterol content and low degree of unsaturation, MBO exhibits a remarkable high oxidative stability with induction period of 36.5 – 46.0 h (Table 5). A subsequent study also indicated that MBO has a high storage stability in which the fatty acid composition of MBO remains unaltered after 24-month of storage period at 30 °C (Mariod et al. 2008). Another study also demonstrated that the incorporation of MBO into sunflower oil could improve the stability of the sunflower oil as a consequence of changes in fatty acids and bioactive components profiles (Mariod et al. 2005). The authors reported that the induction time of sunflower oil increased in tandem with increasing percentage of MBO in the oil blend. These results clearly indicate the suitability of MBO to be used for various food applications especially cooking oil.

MBO was also found to exert antibacterial activity. Mustafa, Mariod, and Matthäus (2008) demonstrated that the crude oil and phenolic compounds-free oil could inhibit the growth of several food-related pathogenic bacteria isolates particularly *Staphylococcus aureus*, *Salmonella enterica* serovar Paratyphi, *Escherichia coli* and *Bacillus cereus* (Mustafa, Mariod, and Matthäus 2008). Therefore, MBO can be applied as a natural preservative to delay the microbial deterioration of meat or fish products.

Diptera

Black soldier fly larvae oil

Black soldier fly (*Hermetia illucens*) belongs to the family Stratiomyidae of the order Diptera. Black soldier fly is an interesting insect species because it can compost the organic wastes such as rotting fruits and vegetables, decaying organic solid waste material or palm kernel meal, thereby minimizing the global food waste burden. The black soldier fly larvae will then convert the biomass nutrients into their own valuable biomass (proteins and lipids). More importantly, they do not transmit diseases to human because the adult flies neither bite nor eat (da Silva and Hesselberg 2020). The insect is commonly detected in areas with compostable materials where they attract the flies to lay eggs. Recently, the mass production of black soldier fly has gained a considerable amount of attention globally owing to their ability to convert a wide range of food wastes and they can be grown up easily with limited land and water (Barragan-Fonseca, Dicke, and van Loon 2017; Matthäus et al. 2019). Black soldier fly is a sustainable source of proteins and fats (Liu et al. 2017). A detailed analysis on the nutrient contents of black soldier fly throughout the entire life cycle (egg, larva, pupa and adult stages) had been examined and reported by Liu et al. (2017).

Fatty acid profile of black soldier fly larvae oil

Black soldier fly larvae oil (BSFLO) is an interesting oil among other insect-based lipids because BSFLO comprises dominantly of medium chain fatty acids (MCFAs) (C8 – C12), accounting for > 50% of the total fatty acid compositions (Table 4). Lauric acid is the major fatty acid detected in the oil. The phenomenon is unusual as most animal fats are often characterized by long chain fatty acid and similar ratio of unsaturated to saturated fatty acids. The antimicrobial activities of lauric acid against a wide spectrum of bacteria and viruses are well reported (Dabbou et al. 2020; Dayrit 2015; Harlystiarini et al. 2019; Khoramnia et al. 2013; Nakatsuji et al. 2009; Yang et al. 2017). Therefore, BSFLO can serve as an active ingredient in pharmaceutical products (healing cream) to provide skin protective properties. The statement is supported by a recent study conducted by Dabbou et al. (2020). They reported that BSFLO is capable of suppressing and delaying the growth of Gram-positive and negative bacteria. Similar antibacterial activity of BSFLO was also reported by Harlystiarini et al. (2019). Besides, the administration of MCFAs could also deliver beneficial health impacts. For instance, MCFA diet could lower the total serum cholesterol and increase the high density lipoprotein cholesterol which translate to reduced risk of cardiovascular disease (Sheela et al. 2016).

BSFLO shows a comparable fatty acid profile to palm kernel fat and coconut fat, the traditionally used lauric-based fats (Ewald et al. 2020; Mai et al. 2019; Matthäus et al. 2019; Spranghers et al. 2017), but deviates significantly from other insect-based lipids. Therefore, BSFLO could potentially replace these conventional lauric-based fats in various food applications, particularly in the development of cocoa butter substitutes. Therefore, more research works can be carried out in bridging the gap. The BSFLO also shows moderate amount of unsaturated fatty acids such as oleic acid (16%) and linoleic acid (7%). The composition of these fatty acids varies depending on the feeding diets (Liland et al. 2017; Matthäus et al. 2019; Ramos-Bueno et al. 2016; Sealey et al. 2011; Spranghers et al. 2017). A study conducted by Liland et al. (2017) reported that the oleic acid and ω-3 eicosapentaenoic acid in BSFLO increased in tandem with the amount of seaweed included in the feeding diet.

Minor constituents of black soldier fly larvae oil

BSFLO is low in cholesterol content which is about 10 – 20 times lower than the animal fat. Besides, BSFLO also has a relatively low concentration of vitamin E compounds (53 – 85 mg/kg) as compared to vegetable oils (Liland et al. 2017; Matthäus et al. 2019). Nevertheless, the sterol content in BSFLO is considerably high with β-sitosterol being the main sterol representative. The high concentration of phytosterol in BSFLO is desirable because the phytosterol compounds could reduce low density lipoprotein cholesterol (Caligiani et al. 2019). BSFLO contains significant amount of Δ5-avenasterol compound (122.1 mg/kg), similar to some functional seed oils such as black cumin seed oil (202 mg/kg) (Kiralan et al. 2014), origanum seed oil (170 mg/kg) (Matthäus, Özcan, and Doğu 2018), pistachio oil (72.6 – 170 mg/kg) (Yahyavi, Alizadeh-Khaledabad, and Azadmard-Damirchi 2020) and sunflower seed oil (170 mg/kg) (Cheikhyoussef et al. 2020). Research study demonstrated that Δ5-avenasterol is a strong antioxidant and can act as an anti-polymerisation at elevated or frying temperature due to the structural element of an ethylidene group in the side chain (Kochhar 2000).

Physicochemical properties of black soldier fly larvae oil

Previous study showed that BSFLO had a high induction period of 50.5 h as compared to black cumin seed oil (19.6 h) (Kiralan et al. 2014), pistachio oil (31.3 h) (Rabadán et al. 2018) and grape seed oil (10 h) (Bjelica et al. 2019). The excellent oxidative stability of BSFLO is ascribed to its fatty acid composition (MCFAs) and high phytosterol content. The TAG compositions determine the crystallization and melting profiles of oils and fats. BSFLO has a high concentration of saturated TAGs such as LaLaLa, LaLaM, LaMM which accounts for 60% of the total TAG content (Matthäus et al. 2019). BSFLO is very similar to coconut oils and palm kernel fats in term of fatty acid composition and TAG profile (Soo et al. 2020).

BSFLO shows two closely separated exothermic peaks at 8.98 °C and 3.57 °C in the crystallization thermogram. The former peak is due to the presence of high melting TAG fractions whereas the latter is attributed by the TAG fractions with unsaturated fatty acids (MOM, LaPO and MPL) (Matthäus et al. 2019). These two crystallization peaks are very similar to the two crystallization peaks ($P_{cry,1} \approx 8.3\,°C$, $P_{cry,2} \approx 2.1\,°C$) reported for commercial coconut oil (Soo et al. 2020) and palm kernel oil (Liu et al. 2019; Norizzah, Nur Azimah, and Zaliha 2018). On the other hand, the melting curve of BSFLO displays a broad melting temperature range with the onset and endset melting temperature recorded at 8 °C and 30 °C, respectively. BSFLO shows peak temperature at 27.2 °C with two small and contiguous shoulder peaks. Similar observation was also detected for palm kernel fat with a single broad endothermic peak from 10 °C to 31 °C and a peak temperature at 25 °C. These results clearly indicate that BSFLO can potentially replace the lauric-based fats in various food applications including confectionary fats, bakery fats, margarine and shortenings owing to its comparable physicochemical properties.

Conclusion and future recommendation

Recent high demand for food and the rapid population growth rate are pushing toward food diversification to meet the massive food demand and ensure food security. Entomophagy is therefore a practical and viable solution to alleviate the current global food crisis and ensure sustainable food production. Insects are highly nutritious, containing all essential nutrients such as proteins, fats, vitamins and minerals. Besides, insect-farming is preferable from an environmental standpoint. Thus, insect-based ingredients can serve as sustainable food alternatives. The present article provides a extensive review on the oils and fats derived from insects of different orders particularly on the fatty acid composition, micronutrients and physicochemical properties. Besides, factors correlated to the nutritional quality of insect lipids are also outlined. Obviously, each insect lipid has its own characteristic fatty acid profile and unique physicochemical properties. For example, MO and LO are high in unsaturated fatty acids, BSFLO is concentrated with MCFAs, SWPO comprises dominantly of α-linolenic acid, MBO has a high level of MUFAs and so on. In addition, insect-based oils and fats are excellent sources of tocopherols, carotenoids and sterols compounds. Therefore, these oils and fats can be incorporated into various food systems including cocoa butter substitutes, cooking or frying oil, margarine, shortenings and others besides exerting beneficial health effects. This review article will help to recognize the potential of insect-based fats and oils in different food applications, replacing the conventional vegetable oils and fats for sustainable food system. However, the physicochemical and sensory properties of the insect lipid incorporated food remain to be uncertain. More research works should delve into this area.

Conflict of interest

The authors declare no conflict of interest with respect to this study.

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