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Global overview of locusts as food, feed and other uses

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ABSTRACT

The term 'locusts' refers to insect species which can aggregate into migratory swarms that cause wide-scale destruction of crops and pasture, causing significant effect to food security. This review assesses the potential of harnessing locust swarms for beneficial uses. Among 21 known locusts, ~10 species have been traditionally consumed by humans or fed to animals for millennia in 65 countries. Their nutritional composition is comparable or superior to that of conventional meat. However, insecticide residues, microbial contaminants and allergens may compromise their safety. Some countries have developed regulations on edible insects, locusts inclusive. Safe and efficient harvest of locusts could offer nutritional and revenue opportunities in many developing countries and serve as a more sustainable management method than the widespread use of insecticides.

1. Introduction

The demand for food by about 10 billion people in 2050 is predicted to increase by 50% compared to 2012 (FAO, 2017). Presently, more than 820 million humans are undernourished, two billion suffer from micronutrient deficiency, and two billion are overweight or obese (Willett et al., 2019). Malnutrition is escalating incidences of diet-related obesity and non-communicable diseases, like coronary heart disease, stroke, and diabetes (Willett et al., 2019). Conventional food sources are increasingly becoming environmentally unsustainable, as they exert a huge pressure on land and water resources, and contribute immensely to greenhouse gas emissions. Animal feed on the other hand accounts for 60–80% of poultry, piggery and aquaculture production costs, with protein ingredients accounting for 70% of the feed costs (Dobermann et al., 2017; Mariod, 2020). The cost of protein ingredients (e.g., fish- and soybean-meal) are exacerbated by their competitive use as human food. Alternative sources of food and protein feed additives are therefore highly needed.

Locust plagues have tormented humans throughout history. Locusts belong to the grasshopper family, Acrididae, in the insect order Orthoptera, which contains 6,787 known species (Cullen et al., 2017). Unlike other grasshoppers, however, locusts can transform between a cryptic solitarious phase, and a swarming gregarious phase that undergoes collective migration. Whereas low density solitary locusts play a critical role in grassland ecosystem functioning through recycling nutrients, shaping plant community structure and serving as a food source for many animals, gregarious ravenous locust swarms migrate for long distances, destroying 80–100% of crops and pasture, exposing bare ground to soil erosion and impacting ~10% of humans (Cullen et al., 2017; Latchininsky et al., 2011; Le Gall et al., 2019; Makkar et al., 2014). Favourable climatic conditions including global warming, and human activities are the primary triggers of locust swarming (Le Gall et al., 2019; Lecoq and Pierozzi Jr, 1995; Peng et al., 2020). During 2019–2021, East Africa, Asia and the Middle East witnessed an unprecedented plague of the desert locust, with record swarm sizes covering 2400 km^2, putting ~20 million people at risk of food insecurity (Roussi, 2020). As a common practice in locust control worldwide, interventions against this plague included massive aerial sprays of broad-spectrum insecticides (Roussi, 2020), which, unfortunately, impact negatively on human and environmental health (Latchininsky et al., 2011; van der Valk, 2006). Other sustainable locust control strategies include biopesticides, monitoring, insect growth regulators, georeferencing using global positioning systems and semiochemical traps (Roussi, 2020). However, most of these are either still undergoing development or not readily available in the market.

This review assesses the potential of harnessing locust swarms for beneficial uses as a a more sustainable management strategy than the widespread use of insecticides. It highlights the global distribution of locust-species, their nutritional value, historical practices of their use as food, feed and other applications, harvesting technologies and regulatory framework. It also points out safety and sociocultural concerns that should be addressed to promote beneficial uses of locusts.

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2. Diversity and distribution

There are 21 known locust-species globally (Cullen et al., 2017; Le Gall et al., 2019; Lecoq and Pierozzi Jr, 1995, Fig. 1), of which 10 (migratory, desert, red, brown, Sahelian, Bombay, Australian plague, Italian, Siberian and South American locusts) have been consumed or fed to animals in 65 countries (Yhoung-Aree, 2010; Kelemu et al., 2015; Costa-Neto and Dunkel, 2016; Mitsuhashi, 2016; Poma et al., 2017). The migratory locust has two subspecies, the Asian migratory locust and the African migratory locust. The desert locust also has two subspecies, a typical swarming northern race in southern Europe, North Africa, Middle East and the Indian subcontinent, and a non-swarming race in southern Africa.

Italian, Siberian and migratory locusts are endemic to the northern Eurasian steppe, but the latter's range extends to the Sahara Desert and southern Europe. Australian plague and African migratory locusts are endemic to Australia, with the latter also occurring in Mainland Africa and Madagascar, Southeast Asia and the Tibetan plateau. Bombay locust occurs in India and Southeast Asia. Sahelian locust occurs in North and Central Africa and the Middle East. Red locust occurs throughout sub-Saharan Africa. Brown locust is endemic to southern Africa. South American locust occurs in South America. Temperature, precipitation, plant species diversity, habitat structure and natural enemies influence the distribution of locusts (Cullen et al., 2017; Latchininsky et al., 2011; Le Gall et al., 2019).

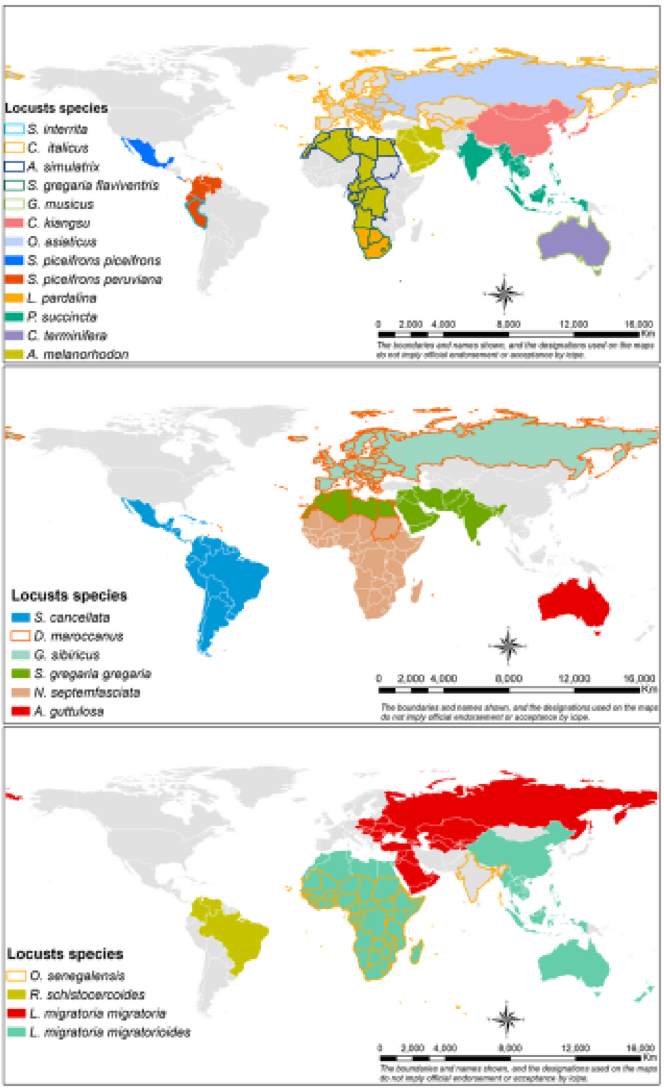

Fig. 1. Global distribution of locust-species. *S. interrita*–Peruvian locust *Schistocerca interrita*; *C. italicus*–Italian locust *Calliptamus italicus*; *A. simulatrix*–Sudan plague locust *Aiolopus simulatrix*; *S. gregaria flaviventris*–Southern African desert locust *Schistocerca gregaria flaviventris*; *G. musicus*–yellow-winged locust *Gastrimargus musicus*; *C. kiangsu*–yellow-spined bamboo locust *Ceracris kiangsu*; *O. asiaticus*–Mongolian locust *Oedaleus asiaticus*; *S. piceifrons piceifrons*–Central American locust *Schistocerca piceifrons piceifrons*; *S. piceifrons peruviana*–Central American locust sub-species *Schistocerca piceifrons peruviana*; *L. pardalina*–brown locust *Locustana pardalina*; *P. succincta*–Bombay locust *Patanga succincta*; *C. terminifera*–Australian plague locust *Chortoicetes terminifera*; *A. melanorhodon*–Sahelian locust *Anacridium melanorhodon*; *S. cancellata*–South American locust *Schistocerca cancellata*; *D. maroccanus*–Moroccan locust *Dociostaurus maroccanus*; *G. sibiricus*–Siberian locust *Gomphocerus sibiricus*; *S. gregaria gregaria*–northern race of desert locust *Schistocerca gregaria gregaria*; *N. septemfasciata*–red locust *Nomadacris septemfasciata*; *A. guttulosa*–spur-throated locust *Austracris guttulosa*; *O. senegalensis*–Senegalese locust *Oedaleus senegalensis*; *R. schistocercoides*–Mato Grosso locust *Rhammatocerus schistocercoides*; *L. migratoria migratoria*–migratory locust *Locusta migratoria migratoria*; *L. migratoria migratorioides*–African migratory locust *Locusta migratoria migratorioides*. The map is triplicated to avoid crowding. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Nutrition and health benefits

Data on dry-matter based nutrient composition is available for migratory, desert, Bombay, and two unspecified locust species from the genus *Schistocerca* (Tables 1–4). This information gives a broad overview of the nutritional value of locusts, but the results are greatly variable due to inconsistencies in the analysis methods adopted, interspecific differences, environmental conditions, life stages, diet, processing methods and if the insects were reared or wild collected. For instance, high carrot content in the diet of farmed migratory locust reportedly increases its fat and vitamin A content, while its protein content decreases with increase in the content of wheat bran in the diet (Salama 2020). There is, therefore, a need to harmonise analysis procedures, and carryout further investigation on the influence of different factors on the nutritional value of locusts.

3.1. Proximate composition and energy

The locust protein, fat and energy contents (Table 1) are comparable to, or higher than those of meat (18–29%, 1–32% and 106–353 kcal/100g respectively; Ahmad et al., 2018; Peng et al., 2020). Although the crude protein levels in locusts are generally high, the presence of chitin may impair its solubility, but this can be enhanced 6-fold under alkaline pH (Brogan, 2018) and through extraction of chitin for other uses (Shahidi et al., 1999). Also, it should be noted that the nitrogen-to-protein conversion factor of 6.25 commonly used to estimate insect protein content, has been found to over-estimate the protein content of migratory locust and other insects by ~17% due to their chitin content (Boulos et al., 2020). Boulos et al. (2020) recommend nitrogen-to-protein conversion factor of 5.33 for more accurate estimation of protein contents of locusts and other edible insects.

3.2. Minerals

Desert locust contains comparable or superior levels of calcium (Table 2) than mutton, beef and pork which contain between 4 and 28 mg/100 g (Ahmad et al., 2018). It contains comparable or higher level of the essential micronutrients iron and zinc than mutton, beef and pork with 1–6 and 2.4–12.5 mg/100 g, respectively (Ahmad et al., 2018; Sun-Waterhouse et al., 2016). Levels of zinc in migratory locust are comparable to those of mutton, beef and pork; and levels of heavy metals in the locust are within accepted limits as in other foods like fruits and vegetables (Ahmad et al., 2018; Poma et al., 2017).

Table 1
Proximate composition of locusts based on percentage dry matter.

Species	*Schistocerca* sp.[a]	Desert locust[b,c,d]			Migratory locust[e,f]		Bombay locust [g]		
Life stage	Undefined	Adult	Adult	Adult	Adult	Adult	Adult		
Location	Mexico	Poland	Sudan	Kenya	Belgium	Thailand	Thailand (markets)		
Source	Wild	Reared	Wild	Wild	Reared	Reared	Raw	Blanched	Fried
Dry matter	–	–	–	–	27	95.3	–	–	–
Protein (%)	61	76.0	53.8	46.3	–	71.2	27.6	20.6	16.6
Fat (%)	17	13.0	29.8	32.3	7.7–11.7	11.4	4.7	6.1	14.8
Fibre (%)	10	2.5	11.0	4.8	–	–	–	–	–
Ash (%)	4.6	3.3	5.1	6.7	–	3.3	–	–	–
Energy (kcal/100g)	–	432.0	527.5	450.8	–	–	157	169	221
Carbohydrate	7	1.7	0.02	9.9	–	–	–	–	–

[a] Paul et al. (2016).
[b] Zielińska et al. (2015).
[c] Khalil (2013).
[d] Kinyuru (2020).
[e] Poma et al. (2017).
[f] Brogan (2018).
[g] Yhoung-Aree (2010).

Table 2
Dry matter-based mineral composition of locusts (mg/100g).

Species	Migratory locust	Desert locust		
Life stage	Adult	Adult	Adult	Adult
Location	Belgium	Poland	Sudan	Kenya
Source	Reared	Reared	Wild	Wild
Calcium	–	70	25.7	208.4
Potassium	–	749	248.0	101.3
Magnesium	–	82	34.6	40.2
Phosphorous	–	–	–	171.0
Sodium	–	173	281.4	27.6
Iron	–	8.4	2.9	4.8
Zinc	3.7–3.8	18.6	–	3.7
Manganese	–	82	–	3.6
Copper	0.5–0.9	6.3	–	–
Barium	–	–	–	–
Aluminium	–	–	–	–
Boron	–	–	–	–
Chromium	0.01–0.02	–	–	–
Lead	<0.003	–	–	–
Cobalt	<0.003	–	–	–
Nickel	0.02	–	–	–
Arsenic	<0.003	–	–	–
Cadmium	≤0.003	–	–	–
Tin	<0.003	–	–	–
Reference	Poma et al. (2017)	Zielińska et al. (2015)	Khalil (2013)	Kinyuru (2020)

3.3. Vitamins

Unlike beef, bacon, mutton, and pork with traces/absence of vitamin A, D and E (Ahmad et al., 2018), migratory and desert locusts contain 0.8–2.4 μg kg^{-1} of vitamin D3 (Oonincx et al., 2018); and desert locusts contains ~0.6 μg g^{-1} and 267.5 μg g^{-1} of vitamin A and E, respectively (Kinyuru, 2020). Migratory locust also contains10–20 μg/100 g of vitamin B12 (Salama 2020), which is 5–10-fold its levels in beef, bacon, mutton, and pork (Ahmad et al., 2018). However, thiamin, riboflavin, nicotinic acid and vitamin B6 which are commonly found in beef, bacon, mutton, and pork (Ahmad et al., 2018), have not yet been detected in locusts.

3.4. Fatty acids and cholesterol

Locusts contain polyunsaturated fatty acids (omega-3 and omega-6) which are essential for prevention of heart disease (Brogan, 2018; Kinyuru John, 2020; Zielińska et al., 2015) (Table 3). Yhoung-Aree (2010) reported 66 mg of cholesterol per 100 g of Bombay locust, which is within the range of 62–81 mg/100 g in mutton, beef and pork, and far less than 261–2200 mg/100 g in animal kidneys, liver and brain (Ahmad et al., 2018). Moreover, Cheseto et al. (2015) demonstrated that desert locust is rich in phytosterols, which impair absorption of cholesterol, thereby lowering its levels in the body and providing cardiovascular protection.

Table 3
Percentage fatty acid composition of locusts based on dry matter.

Species	Migratory locust	Desert locust	
Life stage	Adult	Adult	Adult
Location	Thailand	Poland	Kenya
Source: Wild/Reared	Reared	Reared	Wild
Decanoic acid (C10:0)	–	0.1	–
Dodecanoic acid (C12:0)	–	0.2	0.3
Tetradecanoic acid (C14:0)	–	1.7	2.6
Pentadecanoic acid (C15:0)	–	0.1	–
Palmitic acid (C16:0)	22.3	23.3	26.9
Palmitoleic acid (C16:1)	–	1.8	–
Heptadecanoic acid (C17:0)	–	0.2	–
cis-10-Heptadecenoic acid (C17:1)	–	0.2	–
Stearic acid (C18:0)	10.3	9.3	3.8
SFA total	–	35.3	–
Palmitoleic acid (C16:1n7)	–	–	–
Oleic acid (18:1n9c)	22.4	–	31.7
MUFA total	–	38.4	–
Linoleic acid (18:2n6)	23.0	–	10.1
C18:1n9c + C18:1n9t	–	36.2	–
C18:2n6c + C18:2n6t	–	14.0	–
Linoleic acid (C18:3 n3/6)	–	–	24 .7
α-Linoleic acid (C18:3n3)	13.7	11.4	–
Arachidic (C20:0)	–	0.4	–
Gadoleic/eicosenoic (C20:1)	–	0.1	–
Eicosadienoic C20:2	–	0.2	–
Behenic acid/Docosanoic acid (C22:0)	–	0.1	–
Docosodienoic (C22:2)	–	0.7	–
Omega 3	–	11.4	–
Omega 6	–	14.0	–
PUFA total	–	26.3	34.8
SFA/(MUFA + PUFA)	–	1.2	–
Reference	Brogan (2018)	Zielińska et al. (2015)	Kinyuru (2020)

SFA: saturated fatty acids; MUFA: monounsaturated fatty acids; PUFA: polyunsaturated fatty acids.

Table 4
Amino acid composition of locusts based on dry matter (mg g^{-1} protein).

Species	Bombay locust [a]	Desert locust[b]	Migratory locust[c]	Human requirements[d]
Life stage	Undefined	Adult	Adult	–
Location	Undefined	Poland	Thailand	–
Source	Undefined	Reared	Reared	–
Essential				
Histidine	13.5	20.6	15.6	15.0
Isoleucine	32.7	28.2	29.2	30.0
Leucine	59.5	77.7	50.4	59.0
Lysine	35.7	35.1	36.4	45.0
Methionine	–	8.2	9.0	16.0
Phenylalanine	–	18.7	20.3	30.0
Threonine	22.3	35.5	23.3	23.0
Tryptophan	17.3	–	5.2	6.0
Valine	35.6	56.6	41.8	39.0
Conditionally non-essential				
Asparagine	–	66.1	–	–
Arginine	36.0	39.8	38.4	–
Serine	23.9	33.7	22.2	–
Proline	48.7	67.1	43.1	–
Glycine	48.8	49.4	39.4	–
Glutamic acid	74.4	107.5	62.0	–
Tyrosine	–	33.1	36.3	–
Non-essential				
Aspartic acid	–	66.1	47.4	–
Alanine	92.7	88.8	75.6	–
Cysteine	–	3.6	–	6.0
Glutamine	–	107.5	–	–
Combinations				
Methionine + Cysteine	20.9	11.8	–	22.0
Phenylalanine + Tyrosine	60.0	51.8	–	30.0

[a] Yhoung-Aree (2010).
[b] Zielińska et al. (2015).
[c] Brogan (2018) and.
[d] FAO/WHO/UNU (2007).

3.5. *Amino acids*

Although levels of the two limiting amino acids (lysine and methionine) which are high in cereal grains and legumes, are lower in locusts than the values recommended by FAO/WHO/UNU (2007), their levels are 4–6-fold higher in the locusts than in beef, lamb and pork (Ahmad et al., 2018). Locusts reportedly contain lower levels of lysine, but higher levels of methionine than soybean-meal–a common protein source in animal feed (Makkar et al., 2014).

3.6. *Health benefits*

Desert locust contains important sterols, such as *β*-sitosterol, campesterol and stigmasterol, that help fight high blood pressure and cardiovascular diseases (Cheseto et al., 2015; Sun-Waterhouse et al., 2016). Hydrolyzed desert locust protein inhibits the angiotensin-converting enzyme (ACE), which converts inactive angiotensin I into octapeptide angiotensin II, and inactivates the vasodilator bradykinin, leading to increased human blood pressure (Vercruysse et al., 2005). Locusts could, therefore, serve as antihypertensive ingredients in nutraceuticals or alternatives to synthetic ACE inhibitors like captopril, which causes severe side effects like cough and angioedema (Vercruysse et al., 2005).

Hydrolysates of cooked and baked desert locust proliferate human skin fibroblasts, which are crucial in synthesising components of the skin's extracellular matrix (Zielińska et al., 2015). Advancement in age or other factors that inhibit the proliferation of fibroblasts contribute to outward signs of aging. Therefore, eating processed locusts can reduce symptoms of aging.

4. Potential health and environmental safety constraints of locusts

4.1. *Insecticide residues*

Locust control strategies have evolved from reliance on curative mass spraying of outbreaks with broad-spectrum insecticides to preventive management practices that integrate better understanding of locust biology and ecology, efficient monitoring, and use of more environmentally sound control strategies like biopesticides and high-level technologies such as satellite imagery and geographic information systems (Zhang et al., 2019). Although these preventive management strategies are more rational, effective, economically feasible, and environmentally sound, they still need further technological development before they are applicable on large-scales (Zhang et al., 2019). In the event of a plague, therefore, massive aerial insecticide spraying is still the most reliable method of quickly containing the ravenous impacts of locusts (Roussi, 2020). Toxic chemical residues from these insecticides can, unfortunately, accumulation in locusts, posing a great health risk to consumers and animals (Makkar et al., 2014; Mariod, 2020; Mutungi et al., 2019). For instance, excessive residues of organophosphates were detected in locusts in Arabia and Kuwait (Saeed et al., 1993; van der Spiegel et al., 2013). Also, van der Valk (2006) reported that spraying locusts with insecticides negatively impacted on 30–60% of non-target invertebrates and other aquatic life, including causing massive death of freshwater shrimps. Hence, research into safer alternative approaches for acquiring locust for food/feed (such as mass trapping of unsprayed hopper bands, and mass harvesting of swarms) is critical.

4.2. *Heavy metals*

Reports on contamination of wild collected locusts with heavy metals are scarce, and therefore require investigations. However, slight accumulation of cadmium but none of copper, mercury and lead from the diet have been reported in farmed migratory locusts (Crawford et al., 1996; Zhang et al., 2009). This implies that cadmium may accumulate in locust swarms if they forage on contaminated vegetation. A recent analysis of frozen and dried formulations of farmed migratory locust food products targeting the European food market and produced by Fair Insects BV in the Netherlands, revealed that the levels of Arsenic, Mercury, Lead and Cadmium in the samples were comparable to those set for other foods, rendering them safe for consumption (EFSA Scientific Committee, 2021).

4.3. *Mycotoxins*

Mycotoxin levels in wild locusts have been scarcely investigated. Studies on farmed migratory locust and its food formulations, however, indicated that levels of mycotoxins in the locusts never exceeded established maximum residue limits for foods (De Paepe et al., 2019; EFSA Scientific Committee, 2021). A study by Musundire et al. (2016) on an edible stink bug from Zimbabwe, however, revealed that unhygienic recycling of grain containers to store the insects promotes its contamination with the human carcinogenic mycotoxin (aflatoxin B_1). Attention to hygienic handling procedures to prevent post-harvest mycotoxin contamination of edible insects, including locusts, is therefore paramount.

4.4. *Allergens*

Arginine kinase (a transferase enzyme) and the oxygen transport protein (hemocyanin), known allergens in molluscs and arthropods, are reported in migratory locust (Brogan, 2018; van Huis, 2020). People who are allergic to crustaceans or house dust mites have shown cross-reactivity to locusts and other insects (van Huis, 2020). Therefore, processing and labelling of locust-based products can reduce the risk of allergic reactions (van Huis, 2020).

Spines on the tibia of locusts may cause intestinal constipation (Makkar et al., 2014). However, plucking (removal of wings, legs and antennae) and grinding before use could eliminate this hazard.

4.5. Microbial contaminants

Migratory locust reared in Belgium and the Netherlands, and its products have been reported to exceed hygiene limits for aerobic bacteria and Enterobacteriaceae set for non-insect food products (EFSA Scientific Committee, 2015). The high level of microbial contamination in the locusts was attributed to uncertified insect feed substrates. On a positive note, migratory locust food products produced by Fair Insects BV from the Netherlands were found to contain microbiological values that were within given specification limits for food (EFSA Scientific Committee, 2021). As with other edible insects (e.g., Gatheru et al., 2019 and Labu et al., 2021), heat processing can minimise the risk of microbial contamination in locusts, except for microbial endospores and toxins.

5. Locusts as food

5.1. History of consumption

Locusts have been widely collected during outbreaks and consumed in 65 countries especially in Africa and Asia for millennia (Mitsuhashi, 2016; van Huis, 2020; Weingarten, 2005). The locusts are prepared for eating in different ways including boiling, toasting, roasting, frying, and sun-drying or even raw, usually with wings and legs plucked off in different countries/customs. Their taste relates to that of walnuts and almonds (Weingarten, 2005), with a neutral flavour (Paul et al., 2016; Ramos-Elorduy, 1998). People consume and trade in at least one of the five locusts, namely migratory, desert, red, brown and Sahelian locusts in 26 countries in Africa (Kelemu et al., 2015; Mitsuhashi, 2016). Red locust is consumed in Mexico, Kuwait and Saudi Arabia (Mitsuhashi, 2016). Migratory and Bombay locusts are delicacies in many Asian countries (e.g., Thailand, China, Japan, Philippines, Vietnam, India, Laos, Malaysia and Myanmar); South America (e.g., Mexico); and Europe (e.g., Ukraine and Belgium) (Costa-Neto and Dunkel, 2016; Mitsuhashi, 2016; Poma et al., 2017; Yhoung-Aree, 2010). Australian plague locust is consumed in Australia; Italian and Siberian locusts in China; and South American locust in Brazil and Colombia (Mitsuhashi, 2016).

5.2. Sociocultural issues

Consumption of locusts is influenced by socioeconomic and cultural factors (Sun-Waterhouse et al., 2016). Jewish culture for instance forbids eating all types of insects except locusts, katydids, crickets and grasshoppers in reference to Leviticus 11:20–22 in the Bible. Whereas locusts are easily accepted wholesomely in Africa and Asia, Europeans are more likely to eat conventional foods blended with locust-flour than whole locusts (Mitsuhashi, 2016; Sun-Waterhouse et al., 2016). Young European males are more likely to embrace entomophagy than the elderly and females; and Chinese are more likely to eat locusts than Germans (Sun-Waterhouse et al., 2016). Whereas migratory locust is produced and eaten in the Netherlands, its rating as a potential meat substitute is low (Sun-Waterhouse et al., 2016).

5.3. Harvesting

Most locust swarms are diurnal, therefore, they can be mass harvested at night when they are inactive (Raheem et al., 2019; van Huis, 2021). For instance, Hanboonsong (2010) gives an account of how the government of Thailand resorted to a campaign to promote collecting Bombay locust for human consumption between 1978 and 1981, after different control methods including aerial insecticide sprays failed to contain the locust outbreak. Before then, Bombay locust was not a well-known edible insect in Thailand, but currently, it is one of the most popular edible insects in the country, valued at ~ US$7–8 Kg^{-1}, to the extent that some farmers have resorted to growing maize to feed the locust (Hanboonsong 2010; Hanboonsong et al., 2013). In a recent desert locust plague in East Africa, a Kenyan entreprise, The Bug Picture, embarked on tracking locust swarms to their roosting sites, and quickly mobilised local communities to harvest locusts for sale to the company for processing into protein rich powder for livestock feed formulation (Driver, 2021). In a two-month pilot, The Bug Picture employed 180 harvesters who collected a total of 4.3 tons of locusts and earned a total of US$1,900. A similar strategy was implemented in Pakistan where about 3 tons of desert locust was collected (Samejo et al., 2021). Immature stages of locusts, commonly called hoppers, are also mass-harvestable by driving them into long deep trenches (Sharma, 2014; Mitsuhashi, 2016). Current techniques used for harvesting locust swarms such as sweeping with brooms, hand collecting, large sweeping nets, or trenches can collect only an insignificant proportion of plague populations (Samejo et al., 2021; van Huis 2021). However, we hypothesise that a concerted effort to develop efficient locust harvesting techniques, matching the scale of hundreds of millions of US dollars that are invested in chemical control operations could increase the efficiency of this environmentally friendly strategy with a dual benefit of protecting crop losses while turning locusts into food, feed and other uses. For instance, motorised suction backpacks could help smallholders to harvest locusts at much higher rates (Driver, 2021). Moreover, Lysakov et al. (2019) reported that traps lit by light emmitting diode (LED) lamps were effective in harvesting swarms of unspecified species of locusts in Russia, while Farrow (1974) reported that up to 14,000 individuals of solitary Australian plague locust were trapped per trap per night with 150W UV lamps in New South Wales. The Australian plague locust was repelled by direct light at close range within 3 m, but it was attracted to white surfaces suspended beneath the light source. There's therefore a great opportunity to develop efficient commercial locust light traps as is the case with the edible grasshopper in East Africa (Sengendo et al., 2021).

5.4. Processing

The standard techniques for processing locusts are sun drying and grinding into flour, fermenting with salt, roasting, boiling and frying (Mariod, 2020; Mutungi et al., 2019; Weingarten, 2005). These processing methods can markedly influence nutritional and functional properties of the locusts. For instances, protein from samples of boiled locusts from local markets in Khartoum, Sudan, exhibited 50% digestibility compared to 41% in the fried locust (Mutungi et al., 2019). A decrease in protein digestibility is mainly attributed to the formation of disulfide linkages within the protein matrix which is facilitated by higher temperatures during frying than boiling (Mutungi et al., 2019). Mineral composition, water/fat absorption capacities, bulk density of the locust flour, among other attributes, were also influenced by processing methods. Developing a value chain of locust harvests, therefore, requires underpinning the influence of processing methods on their nutritional profiles, on a case-by-case basis.

5.5. Shelf-life

Packaging and storage techniques that improve shelf-life of locusts need to be researched. In a related edible grasshopper in Uganda, for instance, the post-harvest shelf-life of fresh grasshoppers is 1–2 days (Ssepuuya et al., 2016). However, processing this grasshopper by dry-pan frying, drying, vacuum packaging and opaque storage at room temperature increases its shelf-life to 12 weeks, while chilled storage and vacuum-packed storage of the processed insect at ambient temperature almost doubles the shelf-life to 22 weeks.

5.6. Marketing

The market for edible insects in the US, Belgium, France, UK, Vietnam, Brazil and Mexico was estimated at US$33 million in 2015 and US $142 million in South Korea in 2017 (Dobermann et al., 2017). Thailand imports edible insects worth US$1.14 million annually, among which are locusts (Hanboonsong et al., 2013). Consumers in Thailand highly value locusts at US$7–11 kg^{-1}, unlike conventional meat priced at US $0.8–3 kg^{-1} (Dobermann et al., 2017; Hanboonsong et al., 2013). In many other countries, live and cooked locusts are traded at different market outlets with unmet demands, especially during the off-season (Grabowski et al., 2020; Yhoung-Aree, 2010). The predicted global market for edible insects–which is not segregated between wild collected and farmed–is expected to exceed US$1.5 billion by 2026 (Ahuja and Mamtani, 2020).

6. Locusts as feed

Desert and migratory locusts can replace 25% of dietary protein in fish feed (Makkar et al., 2014). However, the substitution of the locust-meal beyond 25% reduces fish performance, probably due to high chitin levels, which interfere with protein solubility (Brogan, 2018). An unspecified amount of red locust has been added to pig diets with satisfactory growth (Makkar et al., 2014). However, the bacon and pork produced from red locust-based diet had a fishy taste, which was avoidable by discontinuing the diet 3-weeks before slaughter. Locusts reportedly contain lower levels of arginine—an essential amino acid for laying chicken—than soybean (Makkar et al., 2014). However, low-cost synthetic amino acids commonly used in animal feeds can be incorporated into locust-based feeds (Makkar et al., 2014).

7. Other benefits

7.1. Chitin

Chitin is the second most abundant natural biopolymer worldwide after cellulose, which is widely considered a substitute for synthetic compounds used in several feed, food and pharmaceutical products (Shahidi et al., 1999). Chitin can bind dietary lipids, reducing plasma cholesterol and triglycerides, and minimising the risk of hyperlipidaemia related to gallstones (Yhoung-Aree, 2010). Desert locust contains 2% chitin (FAO, 2020); therefore, locusts can be a rich source of chitin for industrial uses.

7.2. Oil

Desert locust oil is richer in omega-3 fatty acids, flavonoids and vitamin E than major commercial plant oils (Cheseto et al., 2020). Moreover, using locust oil to bake cookies could entice non-consumers of insect products to take the first step in entomophagy (Cheseto et al., 2020). Cheseto et al. (2020) recommended future research on better processing of locust oils to minimise off-flavour during baking.

8. Regulations

Recently, regional and national food safety agencies worldwide have initiated extensive reviews and discussions on regulations and guidelines on edible insects. The EU has approved the use of insect proteins in fish feed (Costa-Neto and Dunkel, 2016) and yellow mealworm larva as human food (IPIFF, 2021). The Netherlands and Belgium approve production, consumption and sale of migratory locust; while Switzerland permits their use as food and feed (Dobermann et al., 2017; Halloran et al., 2015; Sun-Waterhouse et al., 2016). Canada permits consumption of insects with a known history of human consumption, provided they comply with the Food and Drugs Act and Regulations (Halloran et al., 2015). However, insects considered novel food in Canada must undergo approval under Division 28 of the Food and Drug Regulations (Halloran et al., 2015). In Thailand, insect-based products for local and export markets must be passed by law through the Food and Drug Administration (FDA); and insect-based exports must be certified by the Royal Forest Department (Halloran et al., 2015; Hanboonsong et al., 2013).

Kenya and Uganda have approved standards on the use of insects as feed ingredients (IDRC, 2019), and human food (KEBS, 2020; UNBS, 2019). This first milestone in Africa is envisaged to reduce animal feed costs and create jobs, especially for women and youth. In Tanzania, locusts are recognized as 'miscellaneous' food in the Food-based Dietary Guidelines (Halloran et al., 2015).

Currently, the use of insecticide sprays to control locusts and other major insect pests is popular because insecticides are more effective and kill the pests faster than other pest-control methods. Convincing policy makers to formulate regulatory frameworks that support adoption of harvesting locusts for beneficial uses requires a strong evidence that the method can effectively reduce locust populations to less damaging levels in a timely manner as insecticides do.

9. Conclusions and recommendations

Locusts are nutritionally as rich as or richer than conventional meat. They contain omega-3 and 6 fatty acids and other sterols which are critical in preventing heart disease; and are low in cholesterol levels. The limiting amino acids lysine and methionine in locusts are 4–6-fold higher than in conventional meat. Locusts are rich in calcium, iron, zinc, and vitamin D3, B12, E and A, and contain safe levels of heavy metals. Locusts have been evaluated as ingredients in fish and pig feed with promising results. They are potential raw materials for chitin, oil and nutraceutical products. Safety concerns in the beneficial uses of locusts are insecticides, allergens and microbial contaminants, but these can be avoided. Efforts are underway worldwide to develop policy frameworks and regulations that support production, use and trade in locusts and other edible insects. We recommend setting value chains to harness locust swarms for beneficial uses by creating mass awareness on their nutritional value, addressing safety concerns, formulating regulations and developing technologies for efficient harvesting and processing of locusts.

Author contributions

JPE and SS conceptualized the study; JPE reviewed the literature and wrote the first draft; SS, CMT and SE acquired the funding; all authors reviewed and approved the MS for publication.

Declaration of competing interest

The authors declare no conflict of interest.

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