Impacts of insect consumption on human health

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Abstract

Edible insects represent an understudied food resource that may promote human health. They characteristically contain ample protein, healthy fatty acids, minerals, and vitamins, and have been touted for their environmental benefits given their efficient resource use. While numerous *in vitro*, animal, and nutrient quantification studies have elucidated a framework of potential health impacts of entomophagy, few have measured direct health outcomes. This review investigates and summarises existing evidence on health impacts derived exclusively from human interventions. A systematic literature search was conducted in three databases: SCOPUS, Web of Science, and PubMed. Out of 1,691 initial results, only nine studies met the inclusion criteria. In these limited studies, insects were shown to have potential to: (1) promote growth and influence iron status when added to complementary foods; (2) modulate gut microbiota with some prebiotic effects; and (3) provide amino acids similar to soya protein. One study also provided isolated evidence that an insect-herb mixture could possibly reduce symptoms of chronic obstructive pulmonary disease when added to routine treatment. Importantly, results reveal a significant lack of human subjects research directly measuring health outcomes from insect consumption. Findings from the included studies indicate that insects are generally safe and offer both beneficial and neutral outcomes compared to other foods. These discoveries, in tandem with extensive evidence from non-human studies, support claims that insect consumption could further enhance health by addressing micronutrient deficiencies or promoting gut health. There are also other plausible health promoting properties of insects that could help ameliorate complications with hypertension and other non-communicable disease. More rigorous and better controlled human intervention trials are fundamental to confirm health benefits and better assess risks associated with entomophagy, while also addressing unanswered questions regarding nutrient bioavailability, the fate of dietary chitin, and *in vivo* activity of bioactive peptides.

Keywords: entomophagy, edible insects, health impacts, nutrition, clinical trial, dietary intervention

1. Introduction

The global food system faces an unprecedented array of challenges, which will have ramifications for human health. Farmers and communities are pressured by climate change, inequitable trade, food waste, supply chain disruptions, and the need to support a growing population while demand for resource-intensive animal products rises (Ranganathan *et al.*, 2016). Animals are an important protein source for many, but livestock production, particularly beef, is one of the largest contributors of greenhouse gas emissions and has also been blamed for other harms to the environment (Poore and Nemecek, 2018). Consequently, novel and

sustainable protein production will be required in the decades to come.

Global food security has improved in recent decades, but advances have not been uniform and challenges remain. An estimated 690 million people faced chronic undernourishment in 2019 (FAO *et al.*, 2020), despite adequate global food supplies. Malnutrition kills more people than AIDS, malaria, and tuberculosis combined (WFP, 2015). Undernutrition weakens the immune system and is responsible for more than 45% (>3 million) of annual deaths among children under five in developing countries (Black *et al.*, 2013). Severe protein energy malnutrition

(PEM) can manifest in muscle atrophy, wasting syndrome, or an increased risk of tuberculosis and gastroenteritis. Anaemia resulting from iron or vitamin B₁₂ deficiency is a major global health risk (Ritchie and Roser, 2017), and low haemoglobin during pregnancy contributes to the between 2.5 and 3.4 million maternal and neonatal deaths that occur each year (Liu *et al.*, 2012; Stevens *et al.*, 2013). In other contexts, overweight and obesity stress healthcare systems as about 650 million people experienced obesity in 2016 (WHO, 2020). The double burden of simultaneous under- and overnutrition also challenges many governments. Increasing insect consumption could help address nutrition-related health problems by safely supplying micro and macronutrients.

While largely overlooked in Western cuisine today, insects are frequently included in traditional dishes across continents. Entomophagy – the practice of eating insects – is not a new phenomenon. Many species have served as an important part of the diet throughout history (Bodenheimer, 1951; DeFoliart, 1995). The practice is highlighted in ancient religious texts, including the Bible (see Leviticus 11:22), and more than 2,100 known edible insects have been identified to-date (Jongema, 2017).

A recent research boom has begun to unpack the many prospects of insects as both food and feed, where previously a paucity of studies existed (Baiano, 2020). The nutritional value of insects has been widely explored, though these data are still sparse relative to the surfeit of edible species and myriad variables impacting nutrient composition. Recent anthropological research has explored insects in human evolution (Lesnik, 2018) and entomologists are even unpacking edible insect genomes (Ylla *et al.*, 2020). Other studies have focused on purported environmental benefits of insect agriculture. There is evidence they require less water, land, and feed than conventional livestock while emitting fewer greenhouse gases (Oonincx *et al.*, 2010; Van Huis *et al.*, 2013).

Generalising nutrient composition across species and growth parameters is difficult, but insects characteristically have nutrient-dense profiles akin to meat – rich in protein and fat, low in carbohydrates. Many species contain ample energy, protein, and healthy fatty acids, while also providing essential minerals, and even some vitamins (Rumpold and Schlüter, 2013). Insects are considered a good source of protein with crude levels comparable to and sometimes even higher than other conventional meat sources (Belluco *et al.*, 2013; Finke, 2002; Melo *et al.*, 2011). The quality of insect protein is said to be high; it is broadly considered bioavailable and relatively digestible (Belluco *et al.*, 2013; Finke, 2015; Verkerk *et al.*, 2007). Insects also provide essential amino acids for human nutrition (Bukkens, 2005; Collavo *et al.*, 2005; Rumpold and Schlüter, 2013), which are particularly valuable in contexts where malnutrition is

problematic. Edible insects are also often a good source of fat with numerous species providing healthy polyunsaturated fatty acids (Womeni *et al.*, 2009) including omega-3s (Paul *et al.*, 2017; Wathne *et al.*, 2018). There is some evidence that modifying insect diets can improve fat composition and ratios (Oonincx *et al.*, 2019). Notably, data related to the nutrient content of insects are often low-quality and limited to within-species variation in proportions of micro- and macronutrients (Payne *et al.*, 2016).

Insects offer myriad potential health benefits that have yet to be fully explored, including those stemming from bioactive compounds with antioxidant or other properties and dietary fibre (Roos and Van Huis, 2017). Insect consumption is not without risks, however. Food safety considerations are important when consuming insects, as they are also potential sources of allergenic, toxic, or antinutrient substances (Rumpold and Schlüter, 2013).

Numerous studies have investigated *potential* health impacts of insect consumption – from nutritional analyses (Belluco *et al.*, 2013; Rumpold and Schlüter, 2013; Womeni *et al.*, 2009) and hypotheses as to impacts on deficient populations (Nadeau *et al.*, 2015), to laboratory studies where insect components are tested on cell cultures *in vitro* (Latunde-Dada *et al.*, 2016) or fed to animals (Bergmans *et al.*, 2020). These studies provide a foundational understanding of how entomophagy *could* influence human health. However, they do not demonstrate causality, nor do they fully explore other key variables driving health outcomes from entomophagy, such as nutritional/immune status of the consumer, presence of antinutrients in insects, processing methods, nutrient bioavailability, allergens, or contaminants.

It remains relatively unclear if and how eating insects improves human health. Are insects unique when compared to other animal foods? Do they contain nutrients or properties that correlate with benefits or detriments to human health? This purpose of this review is to summarise existing evidence from human intervention studies that measure human health outcomes resulting from entomophagy.

2. Methods

Search strategy

To define the scope of this broad topic and investigate health impacts of insect consumption, a systematic review was conducted. The search strategy was developed in consultation with a health sciences academic librarian. Three primary databases were searched, including Web of Science, PubMed, and SCOPUS. The final searches were completed on July 10, 2020. To standardise, two 'AND' categories were applied to basic title, abstract, and

keyword searches in all three databases. An example of a primary search syntax is included in Appendix A. No limits for language, year of publication, author affiliation, or geographic region were applied.

Following the database searches, a secondary search using Google Scholar was conducted to find articles cited in found manuscripts with relevant titles not identified by preliminary searches. Additionally, a repeat of the key search strategy was implemented in Google Scholar with one modification. The names of specific edible insect types (e.g. 'cricket,' 'caterpillar,' 'termite,' 'beetle,' 'weevil,' 'stinkbug,' 'grasshopper,' 'ant,' 'wasp,' 'bee,' 'dragonfly') were added to the first search category to identify articles lacking generic terms such as 'edible insects' or 'entomophagy' in the title or abstract.

Inclusion and exclusion criteria

Following the searches, duplicate results were removed. Next, all titles, abstracts, and keywords were examined for eligibility via the primary inclusion and exclusion criteria. For studies that appeared to meet the inclusion criteria or where no determination could be made based on abstract and title alone, full text articles were reviewed.

All types of peer-reviewed clinical trials, dietary interventions, and acceptability studies whereby human subjects consumed edible insects and health outcomes were measured were included. Studies using insects in various states (raw, whole, processed, modified, added to other foods, or deconstructed into component parts) with or without a control group were included. Studies on insect products (e.g. silk proteins, honey) were excluded. For the purposes of this review, the category 'edible insects' included non-insects arthropods, such as spiders, that are widely grouped with insects in this field.

Search results that were not peer reviewed, such as books and reports, were excluded. Additionally, surveys, animal feeding trials, systematic and narrative reviews, commentaries, consumer taste trials, basic nutrient analyses, and studies not involving direct and monitored human consumption of insects with measured health impacts were excluded. Retrospective case reports outlining health outcomes associated with self-reported insect consumption were excluded.

3. Results

A total of 2,668 citations were collected in the initial searches of Web of Science, SCOPUS, and PubMed. Titles were screened, and a secondary search using Google Scholar for references in key manuscripts and insect-specific studies identified 15 additional papers, making the total 2,681. Systematic deduplication yielded 1,691 citations and 48 manuscripts were pulled for thorough review after screening title and abstract. Of these, nine papers met the inclusion criteria. Figure 1 highlights the selection process.

The nine human intervention studies included in this review were published between 2009 and 2020. They fell into four broad categories: (1) acceptability and nutritional implications of using insects as a component of complementary foods (CFs) (n=5); (2) impacts of insect consumption on gut microbiota (n=1); (3) quality and impact of insects as a protein supplement (n=2); (4) clinical implications of adding an insect granule supplement to routine treatment for chronic obstructive pulmonary disease (COPD) (n=1) (Table 1).

Eight of the studies involved randomised dietary interventions where insect consumption was compared to other treatments, a control, or a placebo. The remaining study was not randomised, but did involve feeding insect foods to human subjects to ascertain acceptability and tolerability (Bauserman *et al.*, 2015b). None of the studies

Figure 1. PRISMA flow diagram outlining screening process for literature review (modified from Moher *et al.*, 2009).

Table 1. Articles included for final review.

Authors	Konyole <i>et al.</i> (2012)
Full title	Acceptability of Amaranth grain-based nutritious complementary foods with Dagaa fish (<i>Rastrineobola argentea</i>) and edible termites (<i>Macrotermes subhyllanus</i>) compared to corn soya blend plus among young children/mothers dyads in western Kenya
Insect type	Termite: <i>Macrotermes subhyllanus</i> (Isoptera: Termitidae)
Study design	Randomised crossover clinical trial + at home dietary intervention (acceptability study)
Location	Makunga Sub-District Hospital, Kakamega County, Western Kenya
Population	Healthy children (6-24 months),
Intervention	(1) 150 ml of WinFood Classic Complementary Food Mix provided to infants for 1 day: Amaranth Grain + 10% edible termites + 3% dagaa (small fish); (2) 100 g flour mix given to mothers to take home. [Compared to two other foods without insects or fish]
Sample	n=57 pairs (child and mother); n=57 consuming insects
Duration	1 day with 1 day washout; 4 week follow-up
Outcomes measured	Tolerance via morbidity data; Maternal and Child Acceptability (ranking & child consumed >75% of serving).
Results	Complementary food with termites was acceptable by the target population with no adverse effects found.
Authors	Skau <i>et al.</i> (2015)
Full title	Effects of animal source food and micronutrient fortification in complementary food products on body composition, iron status, and linear growth: a randomised trial in Cambodia
Insect type	Edible spider: <i>Haplopelma</i> (species unspecified)
Study design	Randomised and single-blinded, community-based dietary intervention
Location	PeaRieng and Sithor Kandal Districts, Prey Veng province, Cambodia
Population	Infants (6 months old)
Intervention	Age-based provision of rice-based complementary food products: WinFood (WF) with small fish and edible spiders. (WF contained 1.8 g spiders per 100 g dry weight.) [Compared to three other formulations without spider]
Sample	n=419; n=106 consuming insects
Duration	9 months
Outcomes measured	Changes in fat-free mass (FFM); change in plasma ferritin and soluble transferrin receptors; changes in anthropometric variables, including knee-heel length.
Results	No difference in fat-free mass increment in insect porridge (WF) compared with control [WF: +0.04 kg (95% CI: 20.20, 0.28 kg); No effect on iron status across the treatments, however iron status deteriorated for all infants over study period for all treatments. No significant differences in anthropometric measurements across treatments.
Authors	Bauserman <i>et al.</i> (2015a)
Full title	Caterpillar cereal as a potential complementary feeding product for infants and young children: nutritional content and acceptability
Insect type	Caterpillar (species unspecified)
Study design	Acceptability study
Location	Rural Equateur Province of the Democratic Republic of Congo
Population	Healthy infants (8-10 months) and their mothers
Intervention	30 g sachet of complementary cereal with dried, ground caterpillar fed to infants daily (actual amount of caterpillar unclear). [Not randomised; no control]
Sample	n=20 pairs (infant and mother); n=20 consuming insects
Duration	7 days
Outcomes measured	Child illness or symptoms as reported by the mother; Maternal acceptability (by rating); Child acceptability (by % consumed); Nutrient content of cereal; Microbiologic assays for food safety.
Results	Caterpillar cereal is safe for consumption (no serious side-effects), has appropriate macro- and micronutrient contents for complementary feeding, and is acceptable to mothers and infants.
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Table 1. Continued.

Authors	Bauserman <i>et al.</i> (2015b)
Full title	A cluster-randomised trial determining the efficacy of caterpillar cereal as a locally available and sustainable complementary food to prevent stunting and anaemia
Insect type	Caterpillar (species unspecified)
Study design	Cluster-randomised controlled feeding trial
Location	Rural Equateur Province of the Democratic Republic of Congo
Population	Infants (6 months old)
Intervention	30 or 45 g sachet of complementary cereal with dried, ground caterpillar fed to infants daily depending on age (actual amount of caterpillar unclear). [Compared with control that did not receive food]
Sample	n=222; n=111 consuming insects
Duration	12 months
Outcomes measured	Compliance with feeding; 24 hour dietary recall; Feeding practices via Infant and Child Feeding Index (ICFI); anthropometric measurements on infants at 6, 9, 12 and 18 months of age; blood indices of Fe status at 18 months.
Results	Supplementation with caterpillar cereal did not reduce prevalence of stunting at 18 months; Infants who consumed caterpillar cereal had higher Hb concentrations than the control group (10.7 vs 10.1 g/dl, $P=0.03$) and fewer were anaemic (26 vs 50%, $P=0.006$); no difference in estimates of body Fe stores (6.7 vs 7.2 mg/kg body weight, $P=0.44$).
Authors	Stull <i>et al.</i> (2018)
Full title	Impact of edible cricket consumption on gut microbiota in healthy adults, a double-blind, randomised crossover trial
Insect type	Tropical house cricket: <i>Gryllobates sigillatus</i> F. Walker (Orthoptera: Gryllidae)
Study design	Crossover clinical trial, double blind, randomised
Location	Colorado, USA
Population	Healthy adults (>18 years)
Intervention	25 g whole cricket powder added to diet daily via muffin and shake. [Compared with control foods without insects]
Sample	n=20; n=20 consuming insects
Duration	2 week intervention (6 weeks total with washout and control)
Outcomes measured	Digestive health questionnaire (self-report); Comprehensive Metabolic Panel; Microbiome changes via faecal DNA; Changes in Microbial Metabolism; Faecal Triglycerides; Measures of Inflammation.
Results	Cricket consumption is tolerable and non-toxic at the studied dose; no changes in excreted bile acids or faecal triglycerides; increase in abundance of the probiotic bacterium <i>Bifidobacterium animalis</i> (5.7 fold); associated with decrease of other bacterium. Cricket consumption also associated with reduced plasma TNF- α . Suggestive of improved gut health and reduced systemic inflammation.
Authors	Vangsoe <i>et al.</i> (2018a)
Full title	Effects of insect protein supplementation during resistance training on changes in muscle mass and strength in young men
Insect type	Lesser mealworm: <i>Alphitobius diaperinus</i> Panzer (Coleoptera: Tenebrionidae)
Study design	Clinical trial, randomised, controlled, single-blinded trial
Location	Aarhus University, Denmark
Population	Healthy young men (18 to 30 years)
Intervention	Ingested an insect-protein bar containing 0.4 g protein/kg (Pro, n=9) within 1 h after each training and 1 h before night sleep on training days. [Compared to isocaloric carbohydrate control bar]
Sample	n=18; n=9 consuming insects
Duration	8 weeks (resistance training 4/week)
Outcomes measured	Strength (leg press and bench press); body composition (via whole-body dual-energy X-ray absorptiometry); dietary records were obtained (three-day registration periods) before and during the intervention period.
Results	No significant differences in body composition and muscle strength improvements observed; compliance indicative of tolerability.

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Table 1. Continued.

Authors	Vangsoe <i>et al.</i> (2018b)
Full title	Ingestion of insect protein isolate enhances blood amino acid concentrations similar to soya protein in a human trial
Insect type	Lesser mealworm: <i>A. diaperinus</i> Panzer (Coleoptera: Tenebrionidae)
Study design	Randomised cross-over study
Location	Aarhus University, Denmark
Population	Healthy young men (18 to 30 years)
Intervention	25 g of crude insect protein ingested postprandially. [Compared to whey, soya, or water placebo]
Sample	n=6; n=6 consuming insects
Duration	4 days
Outcomes measured	Amino acid concentration in blood before and 0 min, 20 min, 40 min, 60 min, 90 min, and 120 min determined using 1H NMR spectroscopy.
Results	Ingestion of whey, soya, and insect protein isolates increased blood concentrations of amino acids (AA) over a 120 min period (whey > insect = soya). Insect protein induced blood AA concentrations similar to soya protein. Higher blood AA concentrations at 120 min post ingestion was observed for insect protein, suggesting it is a 'slow' digestible protein source.
Authors	Konyole <i>et al.</i> (2019)
Full title	Effect of locally produced complementary foods on fat-free mass, linear growth, and iron status among Kenyan infants: a randomised controlled trial
Insect type	Termites: <i>Macrotermes subhyllanus</i> (Isoptera: Termitidae)
Study design	Randomised and double-blind, controlled trial
Location	Mumias Sub-County in Kakamega County, Western Kenya
Population	Infants (6 months old)
Intervention	Provision of: WinFood Classic (WFC) (71% grain amaranth, 10.4% corn, 0.6% soyabean oil, 5% sugar, 10% edible termites, and 3% small fish dry weight); given in age-adjusted daily rations. [Compared to two other foods without insects]
Sample	n=499 pairs (mother and infants); n=165 consuming insects
Duration	9 months
Outcomes measured	FFM accrual, linear growth, and iron status; Changes in FFM, length, plasma ferritin, plasma transferrin receptors, and haemoglobin from 6 to 15 months of age. Secondary outcomes: change in weight, MUAC, head circumference, skinfolds, weight.
Results	WFC insect food was associated with weight gain over the 9 months, predominantly fat free mass. Fat mass was also preserved during the 9-month intervention on all diets. WFC did not differ from the other complementary foods or controls in terms of weight gain or mass. Plasma ferritin decreased, whereas plasma transferrin receptors increased in all three groups over the 9 months indicating an overall deterioration in iron status.
Authors	Hu <i>et al.</i> (2020)
Full title	Effects of compound Caoshi silkworm granules on stable COPD patients and their relationship with gut microbiota: a randomised controlled trial
Insect type	Caoshi silkworm (species unspecified)
Study design	Randomised controlled trial
Location	Jinhua Hospital of Zhejiang University, China
Population	Adults 40-80 with COPD grades II and III and history of 2 or more prior exacerbations
Intervention	Routine COPD treatment plus Compound Caoshi Silkworm Granules (CCSGs) containing 30 g silkworm and 5 g Astragalus, once per day. These granules were given orally, one bag at a time and once a day. [Compared to a control without CCSGs]
Sample	n=40; n=20 consuming insects
Duration	3 months
Outcomes measured	St. George's Respiratory Questionnaire (SGRQ) score and lung function. Microbial abundance from stool samples analysed using 16s rRNA sequencing before treatment.
Results	Safe treatment. Individuals treated with CCSGs showed improved SGRQ scores. No difference in forced expiratory volume / forced vital capacity. Baseline abundance of gut microbiota in patients with the top 10 SGRQ scores differed from the abundance of gut microbiota in those with the lowest 10 SGRQ scores. CCSGs can be considered effective for patients with stable COPD, and gut microbiota may be a new target.

controlled or tracked the entire diet of study participants. Eight studies utilised processed insects integrated into another food – a complementary cereal (Bauserman *et al.*, 2015a,b; Konyole *et al.*, 2012, 2019; Skau *et al.*, 2015), smoothie and muffin (Stull *et al.*, 2018), protein bar (Vangsoe *et al.*, 2018a), or drink (Vangsoe *et al.*, 2018b). One study provided 30 g of silkworm ‘granules’ daily, but processing methods for this product were not specified (Hu *et al.*, 2020). The primary subjects were children (n=1,170). Healthy adults were the next most represented group (n=44) followed by adults with confirmed COPD (n=40). Children and individuals with severe health complications that could compromise the result of these studies were excluded.

None of the studies reported severe adverse health outcomes or a significant increase in morbidity or mortality with insect consumption, even for vulnerable populations. Two studies measured only basic health outcomes, such as tolerance via reported morbidity, which are difficult to interpret and generalise (Bauserman *et al.*, 2015b; Konyole *et al.*, 2012). However, all studies on CFs confirmed that insects are a safe addition to the diet for children. Overall, insect consumption was associated with predominantly positive or neutral results.

Insects in complementary feeding and impacts on nutritional status

The majority (5 out of 9) of human intervention studies evaluated insects as a novel supplement to CF for infants (6 months) and young children (up to 24 months). Two studies took place in Kenya, two in the Democratic Republic of Congo (DRC), and one in Cambodia. Outcomes included anthropometric measurements, acceptability and tolerance, and iron status. All of these studies assessed health impacts of adding insects, along with other locally available ingredients, to CFs. Overall, results suggest insects are an acceptable ingredient in CFs; insect-fortified CFs are comparable to existing CFs. Other observed improvements were not consistent across studies.

Bauserman *et al.* (2015a) conducted a cluster-randomised trial in DRC to determine the effectiveness of complementary cereal including caterpillars (species unspecified) to reduce stunting and anaemia in 175 infants (treatment group n=91). While caterpillar-supplemented cereal did not reduce the prevalence of stunting in children over 12 months relative to a control group (who ate regular diet), caterpillar consumption was associated with an increase in haemoglobin concentrations (Hb levels 10.7 g/dl in treatment, 10.1 g/dl in control, $P=0.03$) and lower anaemia rates (26% in treatment versus 50% control) (Bauserman *et al.*, 2015a).

Building from an acceptability study in 2012, Konyole *et al.* (2019) compared three CFs: (1) WinFood Classic (WFC),

a germinated amaranth, maize, and fish product fortified with 10% termites by dry weight, *Macrotermes subhylanus* (Isoptera: Termitidae); (2) WinFood Lite (WFL), another germinated amaranth and corn-based food not containing insects but supplemented with micronutrients; and (3) corn-soya blend (CSB+), a control corn and soya blend with a vitamin premix. Infants eating all three foods gained weight and there were no differences in body composition (fat free body mass or fat mass) over the 9-month intervention. Weight gained across all groups was primarily fat free body mass. Compared with the CSB++ control, both WFC (with termites) and WFL (with micronutrients) were associated with a decrease in plasma ferritin (WFC 0.6 $\mu\text{g/l}$ (95% CI [0.4, 0.8]) and an increased in plasma transferrin receptors (WFC 3.3 mg/l (95% CI [1.7, 4.9])). The deterioration in iron status was slightly more pronounced among children who ate the termite-fortified food (WFC). Including insects and fish did not impact body composition or promote growth differently than the micronutrient fortified WFL or CSB+ control. Given that none of the CFs improved iron nutritional status, the authors speculate that environmental factors, such as exposure to hazards, enteric disfunction, malaria, and/or breastfeeding may be playing a role in iron absorption (Konyole *et al.*, 2019).

In a similar randomised, single-blinded, community-based trial, Skau *et al.* (2015) demonstrated weight gain in infants who consumed pre-cooked semi-instant porridge with edible spiders (*Haplopelma* species unspecified). Here, infants were fed one of four treatments: WinFood (rice fortified with fish and edible spiders), WFL (rice fortified with small fish only), CSB+ (fortified corn-soya blend), and CSB++ (fortified corn-soya blend with 8% dried skimmed milk). No differences in growth across the four treatments were observed, including changes in fat free body mass and fat mass. No differences in plasma ferritin and soluble transferrin receptor were found between the interventions. However, the WF group had a marginally smaller change in haemoglobin than CSB++ control, and a higher prevalence of anaemia in infants who received the WinFood spider cereal compared to the WFL and the CSB++ corn-soya control (fortified with skim milk) was observed. Anaemia in the insect treatment group was 53.7%, whereas the WinFood Lite was 35.2% and the control was 35.2%. However, anaemia increased across all intervention groups during the study period, likely due to inadequate initial supply of iron in all treatment foods. Overall, locally produced CFs containing edible spiders did not differ from the existing fortified corn-soya blend products.

It is difficult to conduct dietary interventions in food insecure contexts. Not surprisingly, the quality of these complementary feeding trials varied. Some began with heterogeneous baseline participant populations and the full sample of nine studies utilised varying measures of anthropometry. Moreover, environmental factors and

other variables that could impact iron status were not measured. However, Konyole *et al.* (2019) and Skau *et al.* (2015) recruited children of similar ages and included insect-free comparison treatment arms.

Medicinal properties of edible insects

One study explored potential medicinal effects of edible insects. Silkworms have been used historically in traditional Chinese medicine to treat a variety of health conditions, including COPD (Hu *et al.*, 2020; Li *et al.*, 2017). Hu *et al.* (2020) investigated the impacts of taking compound Caoshi silkworm granules (CCSGs), in addition to routine treatment, on COPD patient symptoms and lung function for 3 months. Results were compared with patients who received only routine care. Each CCSG packet given to patients contained 30 g Caoshi silkworm (species unspecified) along with 5 g Astragalus medicinal herb. There was no significant difference in the incidence of adverse events between the two groups ($P>0.05$). Although ingesting silkworm granules did not change measures of lung function, results suggest that it may have improved symptomology, measured via St. George's respiratory questionnaire (SGRQ) ($P=0.02$). The mechanism for action is not clear but may be linked to baseline microbiota among patients. Importantly, it is not feasible to differentiate effects of the silkworm from effects of the Astragalus herb. Additionally, it is likely that other studies reporting medicinal efficacy of silkworms or edible insects are reported in the literature but may not appear in English language journals.

Insects and the microbiome

Only one study in this review assessed the potential for insects to serve as modulators of gut microbiota. In a double-blind, crossover trial, Stull *et al.* (2018) measured the health impacts of consuming 25/g of tropical house cricket, *Gryllos sigillatus* F. Walker (Orthoptera: Gryllidae), per day on healthy adults. Whole ground cricket consumption did not result in toxicity, cause gastrointestinal distress, or yield global disruptions to gut microbiota. Only one small metabolic difference was detected: a slight increase of alkaline phosphatase (ALP) with cricket consumption (95% CI (0.11-0.399) $P<0.05$). Low ALP levels are sometimes associated with malnutrition or malabsorption. However, all participants stayed within normal ALP ranges. No changes were observed across treatment groups in lipid metabolism or phyla-level microbiota composition. Only one significant change in inflammation was observed: tumour necrosis factor alpha was lower after cricket consumption relative to the control (-0.525 (95% CI (-0.93--0.12; $P<0.05$) (Stull *et al.*, 2018).

Five bacterial taxa were significantly increased after cricket consumption and ten were decreased. Little is known regarding all of these taxa, however cricket supplementation (containing ~2 g/day chitin) was associated with a 5.7 fold increase in faecal levels of the probiotic species, *Bifidobacterium animalis*, a 4-fold decrease in faecal *Lactobacillus*, and a 3.5-fold decrease in genus *Acidaminococcus* relative to the control (Stull *et al.*, 2018). Increased levels of *B. animalis* could benefit health, especially through pathogen inhibition. A reduction in probiotic *Lactobacillus reuteri*, is not desirable, but the authors speculate that chitoooligosaccharides may inhibit lactic acid producing bacteria (LAB) and the dietary fibre present in the control diet may have promoted LAB growth. Reductions in *Acidaminococcus* may be desirable, given its association with growth deficits in infants (Gough *et al.*, 2015).

These results are suggestive of potential gastrointestinal and systemic health benefits associated with consuming crickets. However, additional placebo-controlled human feeding trials, along with more *in vitro* studies, are needed to determine mechanisms and long-term health impacts of insects and their component parts on gut microbiota (specifically chitin, specific amino acids, and unsaturated fatty acids).

Interestingly, Hu *et al.* (2020) also considered that microbiota could play a role in how insects impact health via the gut-lung axis. The authors divided participants who consumed silkworm into two groups according to their SGRQ scores (top 10 and bottom 10) and compared their microbiota components at baseline. Significant differences across species value, Shannon value, top 10 levels of phylum, and heatmap of functional predictions were observed. Faecal microbiota may play a regulatory role during administration of silkworm granules, but this is not yet understood.

Insect protein quality

Two studies investigated the quality and utility of insect protein isolate in healthy men. Neither reported unique or novel properties of insect protein. In the first, Vangsoe *et al.* (2018a) investigated the effect of a dietary supplement of insect protein from the lesser mealworm, *Alphitobius diaperinus* Panzer (Coleoptera: Tenebrionidae), on muscle hypertrophy and strength gains during prolonged resistance training compared to an isocaloric carbohydrate supplement. No dietary restrictions were placed on participants. Fat- and bone-free mass improved with both treatments across the study period. No differences in body composition or muscle strength gains were observed between groups. Although the insect protein treatment group consumed more protein on training days than

the carbohydrate group, participants in both groups ate adequate protein outside the intervention. Energy balance variation might explain why no differences in hypertrophy or strength were detected between groups. Ultimately, the authors attribute the change in fat- and bone-free mass to the training program itself and energy consumption, rather than insect protein-supplementation.

In the second study, Vangsoe *et al.* (2018b) investigated the quality of insect protein from the lesser mealworm by comparing postprandial amino acid availability and blood amino acid profiles after participants consumed protein isolate from whey, soya, or insects. Six healthy men were randomised to consume 25 g of protein treatment or a water placebo on four different days. Blood samples were taken before ingesting protein, at the time of ingestion, and then 20, 40, 60, 90, and 120 minutes after. Results indicated a significant rise in blood concentrations of essential and branched-chain amino acids, as well as leucine, over the time period for all protein supplements. This change was greatest for whey, with soya and insects comparable to one another ($P < 0.05$). Insect protein behaved similar to soya protein. Higher amino acid concentrations beyond the 120 min period were observed with insect protein consumption, indicating that insects may be considered a slow digestible protein. Insect protein isolate did not exhibit superior or unique characteristics compared to plant-based soya protein.

4. Discussion

The results of this review indicate a dearth of published human intervention studies investigating edible insects. From those published, entomophagy appears to be safe at the studied doses and offer several potential benefits to human health. Results should not be extrapolated given the number of species studied, small sample sizes, and limited health outcomes measured. Due to the small number of studies per species, no valuable comparisons across insect species can be made at this time. Only one study analysed health outcomes from insect consumption alone and not in combination with other foods (Vangsoe *et al.*, 2018b). Since none of the studies controlled or monitored the complete diet of participants, it is difficult to determine which outcomes resulted from the insects versus other food ingredients or the combination thereof. There is a true need for additional human intervention studies and clinical trials measuring the health impacts of entomophagy.

It would be short-sighted not to put the findings of this review in context with the other extensive research on edible insects from animal studies, *in vitro* experiments, and nutrient analyses. This discussion contextualises the results of the systematic review and highlights other potential health impacts not yet explored through human trials.

5. Improving nutritional status

Micronutrient deficiencies

Insects can be a good source of several essential micronutrients, particularly minerals like potassium, calcium, copper, magnesium, manganese, phosphorous, and selenium (Finke, 2002; Rumpold and Schlüter, 2013; Schabel, 2010). Notably, they also often contain relevant concentrations of zinc and iron (Christensen *et al.*, 2006), with several reporting iron concentrations greater than ground beef or chicken (Finke, 2002; Mwangi *et al.*, 2018; Oonincx and Van der Poel, 2011; USDA, 2018).

The rich micronutrient content of edible insects is particularly relevant in food insecure contexts, where iron-deficiency anaemia is prevalent. As this review demonstrates, the impact of dietary insect iron on iron status is not well understood and outcomes have been inconsistent. In one study, infants that consumed caterpillar-enriched cereal for 12 months had higher iron concentrations and lower rates of anaemia than those that did not (Bauserman *et al.*, 2015a). In two other studies, insect-fortified CFs were not associated with improvements in iron status (Konyole *et al.*, 2019; Skau *et al.*, 2015); however, other ingredients in these foods and/or non-dietary confounders could have influenced iron status.

It remains unclear exactly how well insect iron is absorbed. It is uniquely packaged compared to iron in vertebrates or plants, containing both haem and non-haem molecules. Predominantly, insect iron is found in the non-haem form (ferritin and holoferritin), but insects also contain smaller quantities of haem iron (found in cytochromes) (Mwangi *et al.*, 2018). Several *in vitro* and animal studies suggest that bioavailability of insect iron is good. A recent simulated digestion study assessed the solubility and bioavailability of both iron and zinc from several insect species and compared results with sirloin beef (Latunde-Dada *et al.*, 2016). Iron solubility for insects was greater than steak or whole wheat flour, but bioaccessibility (ferritin concentration in Caco-2 cells) varied by species and was not uniform across foods. Adding insects to wheat flour (1:1) demonstrated better iron and zinc solubility than beef in composite mixtures. It is therefore plausible that adding insects to starch-based diets could help address deficiencies and even increase the bioavailability of native or fortified iron in the starchy foods (Mwangi *et al.*, 2018). In a study of malnourished rats, researchers compared iron bioavailability from two insects, the house cricket, *Acheta domesticus* Linnaeus (Orthoptera: Gryllidae), and the palm weevil, *Rhynchophorus phoenicis* Fabricius (Coleoptera: Curculionidae), a positive control casein, and ferrous sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) diet. After inducing malnutrition, rats were fed supplemented diets for 14 days. During this time, an increase in haemoglobin

relative biological value was observed with both insects, comparable to the control, indicating that these insects are an excellent source of bioavailable iron (Agbemafle *et al.*, 2019). Another study fed palm weevil larvae enriched biscuits to female albino rats for 28 days. Rats fed palm weevil had haematological parameters similar to rats fed the control diet, but their cholesterol concentrations were slightly higher than the control group. No inflammation was observed (Ayensu *et al.*, 2020).

Additional human and animal studies are needed to untangle these contradictory findings and further explore iron bioavailability in humans. Analyses of other variables that impact insect iron absorption, such as its release from the food matrix, effect of food preparation methods, presence of antinutrients, iron form, and systemic factors are needed.

Vitamin B12

There is some evidence that certain insects contain B vitamins such as biotin, pyridoxine, riboflavin, pantothenic acid, folate, and niacin, and B12 (cobalamin) (Nowak *et al.*, 2014; Rumpold and Schlüter, 2013; Schabel, 2010). Major dietary sources of vitamin B12 include meat, milk, animal-sourced foods, and to a lesser extent nori, nutritional yeast, and some bacteria or algae. People eating a majority plant-based diet are often at risk of deficiency. Only a handful of insects have been assessed for B12 content, and most demonstrated negligible quantities. However, the domestic house cricket has been shown to contain an impressive 8 mcg per 100 g fresh weight (FAO, 2017), relevant given the recommended dietary allowance for adults older than 14 is 2.4 mcg per day (NIH, 2018). Some B vitamins are not heat stable and may decrease through processing. The content, stability, and bioavailability of insect B12 requires more research.

Protein and amino acid deficiencies

The quality of insect protein is thought to be good, but there are discrepancies in the literature regarding its digestibility. The two relevant studies in this review did not demonstrate that insect protein from the lesser mealworm is unique or superior to other proteins. Vangsoe *et al.* (2018b) found that postprandial amino acid availability from insect protein isolate is comparable to soya, a high-quality plant protein. But since insects provide animal-based protein, it was expected that they would be more digestible than plant-based protein sources. A previous study in rats showed that termite protein was about 61% as digestible as casein (Phelps *et al.*, 1975); moreover, chitin could modulate protein digestibility (Churchward-Venne *et al.*, 2017). It is possible that processing insects to remove chitin may improve digestibility.

On the contrary, other studies have found variations in insect protein digestibility by species, but relatively high overall levels. In a study of 87 species, protein digestibility ranged from 76 to 96%, higher than most plant proteins but lower than eggs (95%) or beef (98%) (Ramos-Elorduy *et al.*, 1997). Another study measured protein digestibility of the farmed yellow mealworm, *Tenebrio molitor* Linnaeus (Coleoptera: Tenebrionidae), and house crickets fed to rats. Digestibility for both raw (84–92%) and heat-treated insects (84–90%) was high (Poelaert *et al.*, 2018). Others have reported insects having superior or equivalent protein quality compared with soya (Finke *et al.*, 1989; Yi *et al.*, 2013).

Regardless of overall protein digestibility, supplementing inadequate diets with specific amino acids that are deficient could be one means to combat PEM. For example, lysine is the most limiting essential amino acid in corn grain (Alan, 2009). People that get more than 50% of their daily calories from eating corn, such as many communities across Southern Africa, are at risk of developing PEM (Nuss and Tanumihardjo, 2011). Numerous species of insects contain relevant quantities of lysine (Oibiokpa *et al.*, 2018; Sogbesan and Ugwumba, 2008; Stull *et al.*, 2019). Insects are also thought to supply important amino acids that are deficient in other cereal, tuber, and legume-based diets (Bukkens, 2005; Manditsera *et al.*, 2019; Nadeau *et al.*, 2015; Van Huis *et al.*, 2013). A recent study of malnutrition recovery in mice indicated that a tropical house cricket-based diet was comparable to both a peanut- and milk-based diet in terms of body weight recovery, but differed in impacts on immune and metabolic markers (Bergmans *et al.*, 2020). Parker *et al.* (2020) assessed nutrient content of raw, roasted, and groundnut mixed palm weevil larvae in Ghana to supplement CFs. Mixing larvae in all forms with other local foods (e.g. potatoes) was found to supply otherwise deficient lysine to the diet and generate more complete amino acid profiles, which could enhance CFs to help meet nutritional requirements for children (Parker *et al.*, 2020).

It should be noted that insects are not homogenous, and protein and amino acid values in insects do differ by order, species, and rearing conditions. Processing and cooking methods could damage amino acids; Sulphur-containing amino acids such as methionine are particularly susceptible to damage via oxidation depending on temperature and duration of exposure (Hendriks, 2018). More research is needed to understand the quality of insect proteins, the impact of processing on amino acids, and the bioavailability of proteins from insects in the diet.

6. Insect chitin and derivatives

Insects may have health impacts beyond simply providing nutrients; one plausible mechanism stems from the utilisation of insect fibre – a non-nutrient – in the gut. The relationship between insects and the microbiome is not well understood. Only one study in this review assessed impacts of insect consumption on the microbiome (Stull *et al.*, 2018). Another speculated as to interactions between the microbiome and health effects from silkworm consumption on COPD patients (Hu *et al.*, 2020). However, there are several reasons to hypothesise that insects may modulate gut microbiota and therefore indirectly influence health.

Unlike all other animal foods, edible insects contain meaningful levels of dietary fibre, predominantly in the form of chitin, an insoluble fibre. Chitin, a modified polysaccharide (poly-beta-1,4-*N*-acetylglucosamine) with a structure analogous to indigestible cellulose, is the primary component of the insect exoskeleton, respiratory linings, digestive and excretory systems (Clark and Smith, 1935). Through deacetylation, chitin can change structure into more soluble forms, namely chitosan or chito oligosaccharides (COS). COS from other sources are known prebiotics, so it is possible that insect chitin and derivatives could affect human health by selectively promoting the growth of beneficial bacterial species in the intestines.

In the first clinical trial to assess the impact of whole insect consumption on gut microbiota, daily consumption was associated with an increase in the abundance of a beneficial probiotic bacterial species, *B. animalis* (Stull *et al.*, 2018). This particular bacterium has been studied extensively. It helps to inhibit pathogens such as *Escherichia coli* and *Salmonella* in the gut (Collado *et al.*, 2007; Martins *et al.*, 2009). The mechanism of action remains unclear, however. Recent studies demonstrate that several human cell types do produce chitinases (including gastric chitinases) and chitinase-like proteins (Mack *et al.*, 2015; Paoletti *et al.*, 2007) that could break down chitin. In primates, chitinase evolution has been linked to insectivory (Janiak *et al.*, 2017). No evidence clearly explains how chitin is broken down (deacetylated or otherwise) during human digestion, however.

Laboratory and animal studies have confirmed the potential prebiotic effect of insects and indicated that insects can modify the microbiome. Using an *in vitro* simulation model with *T. molitor* insect flour, De Carvalho *et al.* (2019) showed that *T. molitor* insect flour enhanced growth of almost all studied probiotic bacteria, increased production of short chain fatty acids, and helped maintain culture viability even while under nutritional stress (De Carvalho *et al.*, 2019). In another *in vitro* study, digestion resistant constituents from grass grub larvae (predominantly chitin)

were fermented in faecal batch cultures and were associated with an increase in *Faecalibacterium*, which is thought to be beneficial for its anti-inflammatory properties and potential to improve gut health (Young *et al.*, 2020). Animal feeding trials have exhibited similar and more pronounced effects, as in these studies insects can make up a large portion of a controlled diet. Laying hens fed black soldier fly, *Hermetia illucens* Linnaeus (Diptera: Stratiomyidae) larvae meal (in place of soyabean meal) experienced dramatic changes in caecal microbiota, pointing to a prebiotic effect (Borrelli *et al.*, 2017).

Conversely, insect chitin could also inhibit the growth of bacteria, fungi, or other organisms in the gut. For example, a decrease in faecal probiotic *Lactobacillus* was also observed in healthy adults after 2 weeks of consuming cricket (Stull *et al.*, 2018). This is not altogether surprising, given that in laboratory studies, COS was shown to inhibit the growth of *Lactobacillus* spp. (Jeon *et al.*, 2001). In industry, chitosan has been used to prevent beer spoilage by preventing *Lactobacillus* growth (Gil *et al.*, 2004). Antibiotic and antimicrobial properties could also be positive, however. For example, chitin derivatives from various sources have been shown to inhibit growth of pathogens and other less desirable enteric organisms, such as *Clostridium perfringens* (Tsai and Hwang, 2004) and *E. coli* (Chien *et al.*, 2016; Selenius *et al.*, 2018) and even *Vibrio cholera*, and *Salmonella typhimurium* (Fernandes *et al.*, 2008).

Additionally, some evidence suggests that insect chitin could also stimulate activation of innate and adaptive immune cells (Komi *et al.*, 2018), improve glucose tolerance and insulin secretion (Zheng *et al.*, 2018), and exhibit anticancer, antiviral, and antifungal activity (Piccolo *et al.*, 2017). Animal studies indicate that chitin could help control lipid absorption in the intestines, lower total plasma cholesterol and low-density lipoprotein (LDL)-cholesterol, while increasing excretion of triglycerides in faeces (Zacour *et al.*, 1992). Many of these studies are exploratory and more research is needed to understand the properties of insect chitin and all possible health impacts from consumption. Additionally, we need to better appreciate how insects interact with the complex gut microbiome.

7. Other potential benefits

Bioactive compounds

Insects may offer other benefits due to the presence of bioactive compounds. Although none of the articles included in this review specifically investigated bioactive compounds, there is some evidence that these compounds could reduce health risks and boost immune function. For example, insects may contain bioactive compounds that could strengthen immune system function or reduce health risks (Roos and Van Huis, 2017). Specifically,

several publications have confirmed that insects are a good source of biologically active peptides (Nongonierma and FitzGerald, 2017; Wu *et al.*, 2015; Zielińska *et al.*, 2017a,b), which have possible impacts discussed below.

Hypertension and cardiovascular disease

High blood pressure is a key risk factor for stroke, heart attack, chronic kidney disease, disability, and premature death; however it is largely considered preventable (Mills *et al.*, 2016). The angiotensin-converting enzyme (ACE) causes vasoconstriction and subsequently increases blood pressure. Excessive activity of ACE plays a role in regulating electrolyte and water balance, as well as blood pressure (Brunner *et al.*, 1972). Thus, inhibiting ACE activity using drugs (or nutraceuticals) is a common treatment for cardiovascular disease.

ACE inhibitory peptides have been identified in a handful of edible insects, and activity via insect peptides is comparable to some bioactive peptides found in other animal protein sources (Cito *et al.*, 2017a,b). *In vitro* studies have shown that peptides from the silkworm, *Bombyx mori* Linnaeus (Lepidoptera: Bombycidae), have inhibitory activity against ACE as well as the enzyme α -glucosidase (Vercruysse *et al.*, 2005; Wu *et al.*, 2015; Zhang *et al.*, 2016). These studies suggest that insect protein or its hydrolysates could serve as a functional ingredient in supplementary therapeutic foods to treat hypertension or control cholesterol, but human studies are needed.

Metabolic syndrome

Bioactive peptides derived from insects may inhibit enzyme activity associated with metabolic syndrome (Zielinska *et al.*, 2020). Antioxidant and anti-inflammatory peptides in several insects have been observed (Zielińska *et al.*, 2017a), and these peptides have demonstrated antiradical, chelating ions, lipooxygenase, and cyclooxygenase-2 activity. A follow-on study demonstrated that thermal processing the desert locust, *Schistocerca gregaria* Forskål. (Orthoptera: Acrididae), may boost peptide properties (Zielinska *et al.*, 2020).

Type 2 diabetes and obesity

Type 2 diabetes is often complicated by hypertension, which is also a risk factor for stroke, heart attack, heart failure, and kidney disease (Sowers and Epstein, 1995). There are several ways that insects could help manage type 2 diabetes. Synthetic ACE inhibitors are often used to treat hypertension *with* type 2 diabetes, but their side effects are unpleasant and natural product alternatives are desired (Wu *et al.*, 2015). ACE inhibitors from insects may be useful. Inhibiting enzyme α -glucosidase is another therapeutic target for suppressing hyperglycaemia in type 2 diabetes

(Zhang *et al.*, 2016), and only a handful of α -glucosidase inhibitors for diabetes have been identified. Recent research illustrates that peptide fractions from desert locusts could inhibit α -glucosidase to help treat type 2 diabetes (Zielinska *et al.*, 2020). Moreover, glycosaminoglycan derived from the two-spotted cricket *Gryllus bimaculatus* De Geer (Orthoptera: Gryllidae) has been shown to decrease blood glucose, LDL-cholesterol, and alkaline phosphatase levels while reducing oxidative damage in diabetic mice (Ahn *et al.*, 2019).

A few studies have investigated the impact of insects and their bioactive compounds on weight control in mice (Kim *et al.*, 2016; Seo *et al.*, 2017). Results have been favourable, as daily intake of yellow mealworm larvae by obese mice mitigated body weight gain. By reducing fat accumulation in the body and the concentration of triglycerides in fat cells (adipocytes), the insect powder may have contained a bioactive compound that could induce weight loss (Seo *et al.*, 2017). Another study found that extracts of Korean horn beetle, *Allomyrina dichotoma* Linnaeus (Coleoptera: Scarabaeidae), can reduce endoplasmic reticulum stress when injected into the brain tissue of obese mice (Kim *et al.*, 2016).

Insect chitin or chitosan may also impact weight. The influence of dietary chitosan supplements on body weight and fat metabolism is poorly understood. In a recent study, chitosan from fungus was associated with reductions in mean body weight and blood sugar (Trivedi *et al.*, 2016), and a meta-analysis concluded that chitosan supplementation can yield a short- and medium-term effect on weight loss and improvement of serum lipid profiles, as well as cardiovascular factors (Moraru *et al.*, 2018). Human studies are needed to improve our understanding in each of these three dimensions.

Antioxidants

Edible insects are a dietary source of antioxidants. In a comparison of antioxidant capacity of aqueous and liposoluble extracts from insects with olive oil and fresh orange juice, Di Mattia *et al.* (2019) reported that numerous insect species displayed antioxidant capacity values two- or three-fold higher. African caterpillars, grasshoppers, and crickets exhibited the highest levels of reducing power, whereas grasshoppers, silkworms, and crickets demonstrated the highest antioxidant capacity values (Di Mattia *et al.*, 2019).

Processing insects may impact antioxidants. In a study of three species (yellow mealworm, desert locust, and tropical house cricket), processing methods impacted antioxidant and anti-inflammatory activities of the insect peptides. All insects in the study were a good source of bioactive peptides with antioxidant activity, and after digestion and

absorption processes they exhibited high antiradical activity. Moreover, heat treatment positively affected antioxidant properties of the insect peptides (Zielińska *et al.*, 2017a).

Insect antioxidants could also mediate oxidative stress. A study of the free radical scavenging activities of the aqueous extract of lesser banded hornet, *Vespa affinis* Linnaeus (Hymenoptera: Vespidae), demonstrated antioxidant potential, which could mediate therapeutic activities in conditions that are linked to oxidative stress (Dutta *et al.*, 2016). Additionally, edible insect hydrolysates from digested dubia roach, *Blaptica dubia* Serville (Blattodea: Blaberidae), Madagascar hissing cockroach, *Gromphadorhina portentosa* Schaum (Blattodea: Blaberidae), migratory locust, *Locusta migratoria* Linnaeus (Orthoptera: Acrididae), superworm larvae, *Zophobas morio* Fabricius (Coleoptera: Tenebrionidae), and a cricket, *Amphiacusta annulipes* Serville (Orthoptera; Gryllidae), were assessed for free radical-scavenging activity and ability to chelate metal ions. Results demonstrated that these edible insects were a rich source of bioactive peptides with both antioxidant activity and the ability to chelate metal ions (Zielińska *et al.*, 2017b). Reported antioxidants found in insects could help prevent molecular damage, cardiovascular disease, and oxidative stress, but human studies are needed.

8. Health risks

Although the studies included in this review report mostly positive or neutral health outcomes, potential health risks from insect consumption have also been identified. Allergies, food safety concerns associated with microbiological or chemical contamination, and the presence of antinutrients that could impede nutrient absorption are the primary risks currently associated with entomophagy. There is little evidence, however, of disease or parasitoid transmission to humans when insects are handled under sanitary conditions (Van Huis *et al.*, 2013). In general, insects known to be edible are considered safe to eat if they are properly processed and handled.

Allergies

Although excluded from analyses in this review for not meeting the inclusion criteria, more than 250 articles were found that discussed or investigated insect allergens. These studies were not controlled; most were case reports of people eating insects and then falling ill, reviews, or laboratory studies assessing allergens in sera. A review by De Gier and Verhoeckx (2018) provides a comprehensive overview of case reports of allergy following insect consumption, cross-reactive and other proteins involved in insect allergy, and possible alteration of allergenic potential through processing and digestion. Testa *et al.* (2017) also discuss allergies in a review of possible health risks associated with entomophagy. Allergenic effects from

edible insects are difficult to study (Yates-Doerr, 2014), but they have been identified to varying degrees. Insects, like other arthropods, can produce mild allergic reactions in consumers (Ayuso, 2011). There are several known antigenic determinants conserved across arthropods. Cross-reactivity between edible insects and crustaceans has been established (Belluco *et al.*, 2013), and current data highlight the role played by arthropod pan-allergens including arginine kinase and tropomyosin (Ribeiro *et al.*, 2018). Individuals allergic to shrimp may be more likely to be allergic to yellow mealworm than other insects (Broekman *et al.*, 2017), and sera from people with dust mite and crustacean allergies cross-reacted with mealworm proteins (Verhoeckx *et al.*, 2014) indicating that people with dust mite allergies may be allergic to insect proteins. Researchers also found a strong correlation between specific Immunoglobulin E (IgE) levels in the two-spotted cricket, shrimp-specific IgE levels, and responses, indicating that crickets may induce a reaction in individuals with a crustacean allergy (Kamemura *et al.*, 2018). Although uncommon, extreme reactions to edible insects can cause dangerous or fatal anaphylaxis. Anaphylactic shock has been observed with entomophagy in rare cases (Ji *et al.*, 2008; Kung *et al.*, 2011; Okezie *et al.*, 2010).

It is reasonable to recommend that individuals with known shellfish or mollusc allergies avoid entomophagy (Testa *et al.*, 2017). Occupational exposures leading to allergies also pose a threat to people who work closely with edible insects (Mlcek *et al.*, 2014). Double-blind and placebo-controlled trials, food challenges, and research on molecular mechanisms are needed to confirm and further explore this topic.

Food safety

There is no evidence that insect eating is accompanied by more health hazards than eating other animal products (Mezes, 2018). Like all meat products, insects should be properly processed to ensure food safety. Heat treatments are advised to reduce risks (Vandeweyer *et al.*, 2018). Microbial contamination is of particular concern at specific stages of the value chain, including processing, storage, and transportation. Under certain conditions, insect microflora can facilitate the growth of hazardous microorganisms including *Enterobacteriaceae* (Klunder *et al.*, 2012) known to cause food borne illness. Insects can be contaminated via improper handling and processing (Opara *et al.*, 2012) and bacterial spores may survive some cooking methods (Ter Beek and Brul, 2010). Therefore, proper processing, handling, and storage at all times is required to destroy pathogenic microorganisms present on or inside edible insects to ensure food safety (Klunder *et al.*, 2012; Simpanya *et al.*, 2000; Testa *et al.*, 2017).

Chemical contamination and the presence of toxins can threaten food safety. Edible insects can be contaminated by pesticides in their feed source, and some species contain defence-related toxins or repellents (Rumpold and Schlüter, 2013). For example, histamine toxicity and poisoning can occur with eating fried insects. Histidine, found in high concentrations in grasshoppers and silkworm pupae, is decarboxylated by bacteria to histamine, a heat stable toxin that can cause rashes, nausea, vomiting, diarrhoea, headaches, dyspnoea, chest tightness and other complications (Chomchai and Chomchai, 2018). Caution should be followed when consuming the scarab beetle, *Eulepida mashona* Arrow (Coleoptera: Scarabaeidae), in Zimbabwe, which may contain cyanogenic compounds even after traditional cooking (Musundire *et al.*, 2016b). The bioaccumulation of heavy metals in insects, such as lead in grasshoppers (Handley *et al.*, 2007), or presence of mycotoxins such as aflatoxin may pose additional threats (Banjoy *et al.*, 2010; Musundire *et al.*, 2016a); however, more research is needed to quantify these risks.

Malabsorption

Antinutrients identified in some insects, such as phytate, tannin, oxalate, hydrocyanide, saponins, and alkaloids may affect and inhibit the availability of dietary nutrients (Chakravorty *et al.*, 2016; Longvah *et al.*, 2012; Musundire *et al.*, 2014; Omotoso, 2006; Zhou and Han, 2006). Phytic acids, for example, may act as chelators to reduce the bioavailability of minerals. Antinutrients in insects may be absorbed from the feed source or synthesised directly by the insect; thus, rearing conditions could influence this aspect of food safety. Heating and processing may also impact anti-nutrient concentration and nutrient digestibility (El Hassan *et al.*, 2008), and vitamins that are not heat stable (Williams *et al.*, 2016). More research to understand what antinutrients are present in insects and investigate ways to eliminate them before consumption or mediate risk is needed.

9. Conclusions

Edible insects represent a diverse and relatively under-explored food group. There is ample evidence that insects are nutrient-dense, providing valuable macro- and micronutrients for human diets. However, more standardised research, particularly *in vivo* human trials, is needed to ascertain direct health impacts of consumption. Only nine human intervention studies met inclusion criteria for this review, highlighting a dearth of available research, especially given the thousands of edible species to consider. The evidence to-date demonstrates that insects can be a valuable addition to the diet, particularly in food insecure contexts where they may supplement nutrients that are otherwise deficient. They may also serve as a valuable, lower-resource protein in wealthier contexts. Bourgeoning

research on the health impacts of edible insects beyond basic nutrient provision also suggests that insect fibre and bioactive compounds may provide health benefits that warrant further investigation.

Conflict of interest

The author declares no conflict of interest.

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Appendix A

Example primary search syntax used in SCOPUS

TITLE-ABS-KEY ('edible insects' OR 'entomophagy' OR 'edible insect' OR 'minilivestock' OR 'microlivestock' OR 'mini-livestock' OR 'micro-livestock' OR 'farmed insect' OR 'insect cultivation' OR 'insect farming' OR 'insect agriculture' OR 'insect protein' OR 'insect oil' OR 'insect fat' OR 'insect protein isolate' OR 'insect meal' OR 'insect powder') AND TITLE-ABS-KEY ('human trial' OR 'intervention' OR 'clinical trial' OR 'crossover' OR 'health study' OR 'dietary' OR 'dietary intervention' OR 'feeding study' OR 'case study' OR 'epidemiological study' OR 'supplementation' OR 'experimental group' OR 'experiment' OR 'trial' OR 'case control' OR 'case-control' OR 'case study')