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Contribution of edible insects to improved food and nutrition security: A review

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Abstract

The consumption of insects “entomophagy” or insect-based foods is increasingly being recognized as an emerging solution to promote diet diversification and address the multiple burden of malnutrition. Although several studies suggest edible insects as valuable nutrient sources, few have evaluated the effects of processing on nutrient bioavailability and bioaccessibility and provided actual evidence on human nutrition. Moreover, there is limited evidence of their actual contribution to improved food and nutrition security. Therefore, the review evaluated existing evidence on human interventions and the effects of processing methods on bioavailability and bioaccessibility of key nutrients since these directly influence food and nutrition security outcomes. Seven human efficacy studies have been conducted to date and these show limited observable effects on nutrition status therefore more research is required. Findings also suggest that the processing method, insect matrix, composition of the food matrix and interaction with other food components can influence nutrient bioavailability and bioaccessibility. Hence these should be considered during formulation and upscaling for entomophagy and insect-based foods to be viable intervention strategies against malnutrition.

Keywords

Entomophagy; processing; bioavailability; bioaccessibility; nutrition retention

1. Introduction

Malnutrition is a global public health concern, with high levels of undernutrition and micronutrient deficiencies being predominant in developing countries (IFPRI, 2018). The World Health Organization (WHO) (WHO, 2021) estimated that globally, more than 2 billion people suffer from micronutrient deficiency. According to the WHO (WHO, 2021), in 2020, 462 million adults were underweight, 149.2 million children under 5 were stunted whilst 45.4 million were estimated to be wasted. The Multiple Indicator Cluster Survey (MICS) carried out in 2019 by the Zimbabwe National Statistics Agency, showed that nationally, 24% children under 5 are stunted, 3% wasted and 10% underweight (UNICEF, 2019).

High levels of malnutrition hinder the achievement of global nutrition targets set at the Second International Conference on Nutrition (ICN2) to be met by 2025 and the 2030 Agenda for Sustainable Development Goal (SDG) 2 (end hunger, achieve food security and improved nutrition and promote sustainable agriculture (WHO, 2021). SDG target 2.2 calls for ending malnutrition in all its forms (Scott et al., 2020). Undernutrition and micronutrient deficiencies in Africa and Asia are hugely attributed to consumption of less diversified diets characterized by monotonous cereal based diets low or devoid of fruits, vegetables, legumes, pulses and animal-based foods (Praharaj et al., 2021). In these settings the staple cereals also contain antinutritional factors such as phytic acid and phenolic compounds (Gibson et al., 2006). In addition, the corona virus disease (COVID-19) pandemic has contributed to increase in food insecurity and malnutrition (WHO, 2021). This has slowed down global efforts to eliminate hunger and all forms of malnutrition by the year 2030.

Evidence based effective interventions to address malnutrition and contribute to the achievement of the SDGs include dietary diversification, supplementation, commercial food fortification and biofortification (Kairiza et al., 2020, Scott et al., 2020, Praharaj et al., 2021, Meghwar et al., 2021). There is growing interest on the utilization of edible insects as food and feed for tackling malnutrition, particularly in developing countries (Homann, 2015, Nadeau et al., 2015). Insects have impressive nutrient profiles with the potential to deliver affordable high-quality protein, and high amounts of iron and zinc (Gabaza et al., 2018, Verkerk et al., 2007). Hence, insects have an important role towards attainment of resilient food security (Ghosh et al., 2017). It is anticipated that the exploitation of edible insects will have downstream benefits and ultimately improve the livelihoods of local communities. Several funded projects such as the Insects for Food, Feed and Other uses (INSEFF), GREEiNSECT, EntoNUTRI, Agriculture for Food Security 2030 (AgriFoSe2030) and the Insects4Nutrition projects on edible insects and edible-insects based foods have been initiated.

However, the contribution of edible insects and their products to human nutrition is still uncertain. Moreover, the bioavailability of the nutrients in edible insects and their products can be influenced by the processing method, which needs to be considered when implementing food-based strategies. Therefore, the purpose of this review was to evaluate the contribution of edible insects and edible-insects based food products to nutrition outcomes, impact of processing on bioavailability of nutrients in edible insects and edible insect-based products.

2. Methods

2.1. Literature search

A semi-structured literature search was conducted to identify published studies on the contribution of edible insects and their products to nutrition outcomes and the impact of processing on availability of nutrients. Literature search was done in online databases that include Google scholar, Scopus, PubMed Central, Biomed Central, Plosone, and Web of Science to identify relevant published scientific articles. Grey literature, including dissertations, official documents produced at all government levels, and reports and websites from the World Health Organization (WHO), World Food Programme (WFP), Food and Agriculture Organization (FAO) and the European Food Safety Authority (EFSA) were also considered.

For the contribution of edible insects and their products to nutrition outcomes, the following keywords were included in the search, "Edible insects AND human intervention trials", "Edible insects AND randomized interventions", " Edible insects AND randomized controlled trials", "Edible insect products AND randomized interventions", " Edible insect products AND randomized controlled trials". The keywords used to search for relevant literature on the impact of processing on the availability of nutrients included: "methods for processing edible insects", "effects of processing on nutrient bioavailability in edible insects", "effects of edible insects processing on protein digestibility", "effects of edible insects processing on mineral bioaccessibility", "Edible insects AND Processing AND Protein Digestibility", "Edible Insects AND Processing AND Mineral Bioaccessibility", "protein digestibility in processed edible insects", zinc bioaccessibility in processed edible insects", iron accessibility in processed edible insects".

Detailed manual searches including cross-references and bibliographies of available publications were undertaken to find other relevant articles or documents. The inclusion criteria was based on the following; (i) the articles were published in a peer-reviewed journal, (ii) the articles, or part of the articles, were on edible insect consumption, processing practices, (iii) the article, or part of the articles, were on the contribution of edible insects and insect-based products on nutrition status i.e., focusing on human trials, (iv) the papers were in English, (v) the articles were published between the year 1990 to 2021, as this is the period when relevant research on edible insects was published.

The selection led to 98 relevant articles and full versions of these documents were read and judged again using the inclusion criteria, resulting in a final body of literature of 17 articles.

[Figure 1]

3. Results and Discussion

Seven relevant articles were identified on nutrition status (Table 1) and ten on the effects of processing on the bioavailability of nutrients in edible insects and edible insects-based products (Table 2).

3.1. Contribution of edible insects and edible insect-based food products to nutrition status

Several studies show that various edible insect species are a valuable source of nutrients i.e., protein, energy, fat, vitamins and micronutrients particularly minerals, which are comparable with most fresh meat sources (per fresh weight) (Akullo et al., 2017, Van Huis, 2003). Most of the nutritional compositions are reported based on analysis of raw insects (Manditsera et al., 2019). However, nutrient composition is only a proxy to effects on human health (Payne et al., 2016). Moreover, most studies check for acceptability of the edible insects (Bauserman et al., 2015b, Konyole et al., 2019) and make inferences on the contribution of insects to human health and nutrition without further nutrition efficacy trials (Manditsera et al., 2019, Kinyuru et al., 2010). Only a few human nutrition intervention trials have been published (Payne et al., 2016) and there is limited research on the contribution of edible insect-based food products on nutrition outcomes (Table 1).

[Table 1]

3.1.1. Characteristics of the reviewed studies

Omollo (2014) studied the effect of improved complementary foods on lean body mass, essential fatty acids and gross motor development in infants. These foods consisted of 10% termites (*Macrotermes* subhylanus). They found no significant differences in essential fatty acid profile, lean mass accrual and gross motor milestone attainment. However, a significantly greater concentration of arachidonic acid was found in infants that consumed the termite-based complementary food, which could also have been from the small fish included. Arachidonic acid is an important fatty acid in the brain crucial for early neurological development and neurological health (Ayensu et al., 2019). Considering the importance of arachidonic acid in brain development, this outcome can be explored further. Since the termite-based food had similar outcomes with the control groups, termites could be utilized as part of complementary foods where they are culturally acceptable (Omollo, 2014). In the same trial, Konyole et al. (2019) further explored the effect on fat free mass (FFM), linear growth and iron status and found no significant differences in FFM gain and length in the insect-based trial group compared to the other 2 non-insect-based food trial groups. However, weight gained in all 3 groups was mainly FFM. In both studies, the edible termites (*Macrotermes subhylanus*) constituted only 10% of the meal, which may have been too small to effect any changes in nutritional status. Using different insect-food blends could be beneficial in identifying the optimum level that yields high nutritional value and contributes to observable nutritional outcomes (Awobusuyi et al., 2020).

A study by Bauserman et al. (2015a) (Table 1) found higher hemoglobin and fewer anemia cases in the intervention than the control group. Including such diets that reduce anemia cases could be beneficial to low socio-economic communities and in developing countries for both maternal and child health (Kinyuru et al., 2013a, Solomon and Prisca, 2012, Zielińska et al., 2015), where at least 40% of preschool children are believed to be anemic (Zielińska et al., 2015). However, no effects on stunting and no difference in estimates of body iron stores were observed. The authors concluded that supplementing infant porridge with caterpillar might have a beneficial effect on iron status but not on stunting due to multiple etiologies responsible for stunting. However, the authors did not specify the species used. Skau et al. (2015) did not find any difference in FFM increment and no effect on iron status when studying the efficacy of two (2) rice-based complimentary food products i.e., one fortified with minerals and vitamins and one unfortified but with more fish and edible spiders (*Haplopelma* species) . The spiders constituted only 1.8% of the meal. Though this may have been too low to cause an effect or to contribute to the iron status, this study demonstrated that the locally produced complementary foods were just as good as or equal to the commercially fortified foods. However, it did not show that consumption of edible insects proffered separate advantages.

Homann (2015), on cricket (*Acheta Domesticus)*-based biscuits, found no difference in gut microbiota as well as percent change in weight and BAZ (BMI-for-age z-score). However, this was a small study (Table 1) that was not powered to detect the effect of cricket consumption on anthropometric indices. Furthermore, the follow up period was too short (4 weeks) to fully assess changes in the anthropometric indices as older children have a less steep growth curve and the quantities consumed per day (98-102 g with only 10% cricket powder) were low. Stull et al. (2018) also investigated the impact of edible crickets on gut microbiota but in this case, adults where given breakfast shakes (Table 1). Findings suggested that eating crickets could improve gut health and reduce systematic inflammation as the cricket powder supported the growth of *Bifidobacterium animalis.* However, more research, with longer duration could enable analysis of the effects, any confounding factors, and the underlying mechanisms.

The study by Kipkoech (2019), also used cricket-based porridge. The porridge was shown to improve the nutritional status of children, which could be beneficial in developing child feeding products and in child feeding programs. The protein content in the crickets was found to be higher than the protein content in milk and the nutrition intervention showed that cricket powder is a good alternative when compared with the traditionally used milk powder.

3.1.2. Contribution to nutrition outcomes

A review of the human nutrition efficacy trials presented in Table 1 shows that most of these studies have only been published since 2014, which shows an interest in empirical evidence on the contribution of edible insects to human nutrition. Most of these studies (6/7) have also been conducted in Africa, which could be attributed to the need for providing high-quality and nutritious diets in the quest for food and nutrition security (Kinyuru et al., 2013b). Moreover, most of the studies (6/7) involved infants and children, with only one article involving adults. The state of children's malnutrition in the 21st century has shown that more young people and children are surviving but not thriving and the agenda of The State of the World's Children 2019 report was set to putting children's nutrition rights first (UNICEF, 2019). Crickets and termites, which were used in a majority of the studies are rich sources of proteins, fiber, fats (essential fatty acids), vitamins and minerals (zinc, iron), necessary for growth and development, especially in children (Ayensu et al., 2019, Montowska et al., 2019). However, the human trials did not show any observable effects of the edible insects on the nutrition outcomes, when compared to the control groups (Table 1, Payne et al., 2016).

Comparison of the three studies Bauserman et al. (2015a), Konyole et al. (2019) and Skau et al. (2015) assessing the effect on iron status and hemoglobin levels suggest that the caterpillar species used could have had a better iron content than the termite and spider species. Various studies have reported varying content of caterpillars depending with the species, e.g., iron content for *L. litoralia* as 19.5g/100g (Solomon and Prisca, 2012), *Cirina forda* as 12.85mg/100g (Paiko et al., 2014) , mopane caterpillar between 31 - 77 mg/100 g (Zielińska et al., 2015). However, regarding the termite species studied, i.e., *Macrotermes subhylanus*, Kinyuru et al. (2013a) found the iron content to be 53.33 ± 1.46mg/100g. It is crucial for the caterpillar and Haplopelma species to be identified for correct comparisons on the nutrient compositions and their effect on nutrition outcomes to be made. Also, Bauserman et al. (2015a) did not specify the quantity or ratio of caterpillars added. The meal could have been high in the insect proportion leading to an effect on iron status. It is also important to note that the amount of iron is also dependent on its bioavailability (Zielińska et al., 2015) and the soil type could be a factor in the iron content in termites (Kinyuru et al., 2013a). Stull (2021) suggested that dietary confounders could influence iron status. For example, the reduction in hemoglobin and iron status in all three groups in the study by Konyole et al. (2019) could have been attributed to the inhibitory effect of amaranth, which was a main ingredient in the two meals. Although the amaranth was germinated to improve the bioavailability of minerals, the inhibitory effect may have persisted in the final meals. This could have implications in future efficacy studies on the choice of carbohydrate source in insect-based cereals. As such, it may be important to consider the use of bio fortified cereals in future studies to improve the overall bioavailability of minerals such as iron and zinc (Kumar et al., 2019, Lockyer et al., 2018).

Two studies Homann (2015) and Stull et al. (2018) studied the impact of crickets on gut microbiota, with Homan finding no differences whereas Stull et al. (2018), showed a growth of *Bifidobacterium animalis*. The studies where done for different populations (children vs adults), with differing products (biscuits vs breakfast shakes) and sample size (54 vs 20). More studies are required to draw conclusions on the impact of edible insects on gut microbiota. This is because some in vitro studies have shown a positive impact on microbiota of e.g., insect fortified foods (de Carvalho et al., 2019, Young et al., 2020).

Due to the limited evidence on the existing efficacy trials, the actual impact of edible insects to nutrition outcomes is still yet to be understood. As shown in the review, the outcomes have been inconsistent and the mechanisms by which the nutrients are absorbed are unclear. The study design, accuracy of demographics, other factors other than dietary deficiencies, and low quantities consumed could have contributed to the lack of observable effects (Bauserman et al., 2015a, Homann, 2015). Moreover, depending on the insect species, the nutritional content of the edible insects widely varies within and across insect species owing to the diet, development stage, gender, season, geographical location and environmental factors (Dobermann et al., 2017, Kinyuru et al., 2010, Madibela et al., 2009, Bukkens, 1997). From the reviewed studies, only Kipkoech (2019) assessed the impact of the development stage/harvesting maturity on nutrient content and reported optimum levels of protein, mineral, and fat between weeks 9-11. This could have contributed to the improved anthropometric indices and significant differences in fatty acid and haemoglobin levels (Table 1).

3.1.3. Implications for further research

Variations in nutrient composition due to processing techniques, bioavailability/bio-accessibility, and the influence of processing and storage on nutritional composition are also important (Babarinde et al., 2020). Moreover, with the porridge developed by Kipkoech (2019) showing positive outcomes, it could be beneficial to consider the processing methods and the composition of the food matrix. Fernández-García et al. (2009) indicated that the composition of the food matrix and the interaction with other components directly influences the bio-accessibility of the nutritional compounds and that processing modifies the food matrix thus either enhancing/increasing or decreasing nutrient bio-accessibility. Despite the promising nutritional profiles of edible insects, most studies did not demonstrate a clear beneficial effect, which warrants further investigation to clarify the iron absorption and nutrient bioavailability from different blends, and to isolate the specific impact of the edible insects (Konyole et al., 2019). With the reported high nutrient profile and global popularity of edible insects, more high quality studies using different recipes are required to improve their ability to reduce protein energy malnutrition, mineral deficiencies and improve body composition in vulnerable groups (Van Huis and Dunkel, 2017). This therefore calls for an assessment of the impact of processing on the bioavailability of nutrients from edible insects.

3.2. Impact of processing on availability of nutrients.

Most edible insects are subjected to processing prior to consumption and production of edible insects food products (Mutungi et al., 2019). The traditional processing methods include sun drying, roasting, boiling, frying (Alamu et al., 2013), steaming, stewing (Feng et al., 2018), smoking, curing (Melgar-Lalanne et al., 2019) and fermentation (Kewuyemi et al., 2020). Other modern processing methods include freeze-drying, oven-drying, fluidized bed drying, and microwave-drying (Melgar-Lalanne et al., 2019). Generally, the processing of food usually causes modifications in the food matrix which can enhance or decrease the nutrient bioaccessibility (Fernández-García et al., 2009). According to Williams et al. (2016) insect processing has the potential to improve the nutritional quality, safety, taste, and shelf life. However, in some instances it leads to the formation of anti-nutritional and/ or toxic components (such as the D-enantiomers of amino acids and Maillard products) (Friedman, 1996) as well as the reduction in some nutritional properties (Kinyuru et al., 2010, Manditsera et al., 2019). Kinyuru et al. (2010) highlighted that some of the traditional processing methods are usually uncontrolled, and hence have negative effects on the nutritional content and quality of insects. A number of studies have reported contradictory effects of processing on nutrient composition and bioavailability of nutrients in edible insects depending on the insect species and geographical region (Mutungi et al., 2019). It is therefore important to review literature to get in-depth insights on the impact of processing on nutritional content and quality of edible insects and their products. Such an understanding is important in designing edible insect-based products and also for optimizing nutrition bioavailability. Table 2 shows a summary of the different processing methods and their effects on nutrient availability in edible insects. Protein, zinc and iron are shown (Table 2) as they are the main nutrients affected by processing.

[Table 2]

3.2.1. Protein content and digestibility

The reviewed studies revealed that degutting, boiling, roasting, frying, oven cooking, vacuum cooking, drying, autoclaving and fermentation have an effect on the protein content and digestibility. Degutting, which is done to some insect species, is the removal of extraneous matter, digestive remains in the insects and separation of unpalatable parts by removing the wings, legs and head depending on the species (Mutungi et al., 2019), and can influence nutrient content. For example, degutted mopane worm (*Imbrasia belina*) had a higher concentration of protein and *in vitro* true dry matter digestibility as compared to the undegutted samples (Madibela et al., 2007). This finding is corroborated by Lautenschläger et al. (2017), who reported a significant increase in the protein content of edible caterpillar (*Imbrasia epimethea*) after degutting. The increase in protein content after degutting was associated with the removal of the carbohydrate-rich content of the gut thereby resulting in a relatively larger amount of the remaining constituents. In addition, Madibela et al. (2007) found that degutting results in a significant reduction in the condensed tannins mostly known for their antinutritional properties.

Manditsera et al. (2019), investigated the effect of boiling and roasting on the protein content and digestibility of beetles (*Eulepida mashona*) and cricket (*Henicus whellani*). Boiling (30 min and 60 min) was reported to cause a reduction in the protein content and digestibility of both beetles and cricket, while roasting caused a reduction in the protein digestibility of crickets only. This was in agreement with the study on boiling (60 min) and roasting of mopane worms *(Imbrasia belina)* which caused a reduction in the protein content and *in vitro* true dry matter digestibility (Madibela et al., 2007). However, a study on edible caterpillars *(Imbrasia epimethea*) another member of lepidoptera family, showed that boiling for 30 min had no significant effect on the protein content (Lautenschläger et al., 2017). Conversely, the boiling (1 min) of mealworm *(Tenebrio molitor* L.) caused a significant increase on the *in vitro* crude protein digestibility (Megido et al., 2018). These studies therefore highlight that the boiling duration has an impact on the nutrient composition and availability. The observed reduction in the protein content after boiling has been associated with the hydrolysis of parts of connective tissue and other proteins (Zhang et al., 2014) as well as the migration of soluble proteins into the insect exudate (Megido et al., 2018).

Mealworm frying resulted in a significant reduction in the protein content only whilst vacuum cooking and oven cooking increased the digestibility of crude proteins (Megido et al., 2018). However, Babiker (2008), showed that flours from previously fried and boiled Sudanese tree locusts (*Anacridium melanorhodon)* were both rich in protein (67.75% and 66.24% respectively) and frying reduced the *in vitro* protein digestibility. The low *in vitro* digestibility values observed in fried flour samples were attributed to the presence of phytates which complexed with proteins rendering them unavailable. The study on adult house crickets (*Acheta domesticus*) and mealworm larvae (*Tenebrio molitor*), showed that oven cooking and autoclaving did not affect the protein content but caused a significant reduction in the *in vitro* crude protein digestibility (Poelaert et al., 2016). Also, toasted, fresh dried and toasted-dried green and brown grasshopper (*Ruspolia differens*) had low *in vitro* digestibility as compared to the unprocessed (Kinyuru et al., 2010). However, all the three processing methods did not have an effect on the termite (*Macrotermes subhylanus*) *in vitro* digestibility.

The fermentation of dried silkworm (*Bombyx mori)* larvae using *Aspergillus kawachi* as the starter culture caused a reduction in the total free amino acid amounts (Cho et al., 2019). Specifically, a reduction was recorded in serine, glutamic acid, lysine, histidine, arginine and glycine in the fermented silkworm. However, in a study on seasoning sauces using mealworm (*Tenebrio molitor)* larvae, fermentation using *A. oryzae and Bacillus licheniformis* resulted in a 1.5–2 times increase in the essential and nonessential amino acids, as well as amino acid derivatives (Cho et al., 2018). Mendoza-Salazar et al. (2021), in their study on fermentation of flours from mealworm (*Tenebrio molitor*) and grasshopper (*Sphenarium purpurascens*) using the *lactococcus lactis* strains, reported an increase in the protein content, degree of hydrolysis and the peptide profile suggesting partial hydrolysis of the proteins. Furthermore, the fermentation produced bioactive compounds with potential antioxidant and antihypertensive activities. Differences resulting from fermentation could be due to the strains used in the fermentation process. For instance, Sudo et al. (1995), reported that for mycelial growth, the *Aspergillus kawachi* needs carbon, nitrogen, minerals, and oxygen, hence the amino acids and minerals in unfermented silkworm larvae are consumed during fermentation resulting in a decrease in the amino acid contents.

From the different studies reviewed in Table 2, it can be concluded that the processing method can decrease or increase the protein digestibility mainly depending on the processing conditions.

Exposures to denaturation temperatures such as those used during boiling and oven cooking may either increase or decrease the protein digestibility (Boye et al., 2012). The change in the digestibility of the protein is mainly dependent on the protein transformation (structural changes such as denaturation, crosslinking and interaction with lipids and carbohydrates) during the heating process or the processing method. Apart from that, use of high temperatures can also inactivate antinutritional compounds such as trypsin inhibitors (Opstvedt et al., 2003). Increase in digestibility of native proteins can occur through the unfolding of the polypeptide chain thereby making the protein more susceptible to digestive enzymes (Opstvedt et al., 2003). However, in most cases – as observed in the above studies – the digestibility is reduced; this is mainly due to the occurrence of reactions that are induced between and among amino acids that cannot be hydrolyzed by digestive enzymes (Opstvedt et al., 2003) such as the disulphide bond formation within the protein (Mutungi et al., 2019).

3.2.2. *Mineral content and bioaccessibility*

A few studies have investigated the effect of processing on the mineral availability in edible insects (Manditsera et al., 2019, Madibela et al., 2007, Babiker, 2008). Table 2 shows that processing method can influence the content and bioaccessibility of zinc and iron. A study by Madibela et al. (2007), showed that both boiling and roasting had an negative effect on the zinc content of mopane worms. Though no effect on zinc and iron content was reported by Manditsera et al. (2019) in both beetles and crickets, the bioaccessibility of iron and zinc in the boiled beetles decreased. Contradictory results were reported in boiled Sudanese tree locusts flour which showed higher zinc and iron contents and extractability compared to the fried flour sample (Babiker, 2008). Cho et al. (2019), reported a 15.8% and 36.7% reduction in zinc and iron content in fermented silkworm as compared to the unfermented ones.

Variations in the bioaccessibility of minerals between insect species is related to the insect matrix. Also, since minerals such as zinc and iron are complexed with other food constituents these can also differ between the minerals and the insect species (Manditsera et al., 2019). For instance, Gharibzahedi and Jafari (2017) reported that, during processing bivalent minerals form interactions with proteins and carbohydrates thereby decreasing their bioaccessibility. In addition to this, as a result of heating reactions, various compounds can be formed, which in most cases are more resistant to digestion with the ability to bind minerals (Manditsera et al., 2019). High amounts of insoluble dietary fiber, which binds to iron and zinc, will also reduce their bioaccessibility.

3.2.3. Advantages, disadvantages and possible influencing mechanism

Generally, the type of the processing method used has an effect on the nutritional quality (i.e. the value, digestibility, bioavailability) and properties of the final edible insect product. Cooking of edible insects enhances their digestibility and bioactivity of the proteins in the digestive tract as well as the sensory quality through the formation of aromatic compounds (Melgar-lalanne et al., 2019). Also, foodborne and degradative enzymes are reduced during cooking thereby increasing the shelf-life of the insect-based products. However, during these thermal/heat treatments processes (cooking, boiling, drying, roasting and toasting) some nutrients (e.g. protein, minerals) can be lost through solubilization, leakage, inter- and intra-biochemical reactions or the formation of a new by- products (Megido et al., 2018). In some cases, the denaturation of protein, destruction of the amino acid or their modification and Maillard reactions can also occur (Melgar-Lalanne et al., 2019). Although, the nutritional composition can be reduced by thermal treatments, boiling for instance inactivates the insect's endogenous enzymes that are capable of degrading or spoiling the product (Melgar-Lalanne et al., 2019) as well as decreasing the initial microbial load (Wynants et al., 2018). Processing techniques such as roasting reduces the moisture content and water activity present in the insect thereby slowing down the microbial growth, chemical and enzymatic reactions subsequently increasing the product's shelf life (Liceaga, 2021).

The advantage of using fermentation is that specific microbial cultures can be chosen and used to ferment macromolecules present in the insect into desirable and preferred metabolites such as amino acids amongst others (Liceaga, 2021). Kewuyemi et al. (2020), reported that fermentation results in insect-based products with appealing sensory properties and improved nutritional quality. It is important to note that, the substrate composition of the fermentable substrate and selection of bacterial or fungal starter cultures should be considered during fermentation. Since insects are rich in proteins, that can be more difficult to degrade (Mouritsen et al., 2017), starter cultures to be chosen must be able to utilize both inorganic and/or organic sources of nitrogen to conduct a suitable substrate metabolism and acidification (Singh et al., 2017) so as to avoid compromising the nutritional quality.

3.2.4. Insights from the reviewed literature

The studies described show that prior to choosing the processing method for an insect, it is important to understand the nutritional composition. An insect with high protein content is likely to have reduced bioaccessibility after heating. Furthermore, since time variations – e.g. boiling for 1 min to 60 min – seemed to have different effects on nutritional bioavailability, it is important to optimize the edible insect processing method to maximize nutrient availability prior to upscaling. Generally, there is a lack of studies on bioaccessibility of other nutrients such as fatty acids and the presence of antinutritional factors, as most studies are concentrating on protein and mineral (iron and zinc) bioavailability. There is therefore a need to investigate effects of processing on other nutrients prior to upscaling the utilization of edible insects.

4. Conclusion and Recommendations

Edible insects and their products are a potential intervention strategy against malnutrition. Edible insects and their products are a good source of proteins, zinc and iron amongst other nutrients, but their effect on human nutritional status remains uncertain as the existing human intervention studies provide limited evidence on the observed impact on human nutrition. Moreover, processing of the edible insects and their products can influence the nutrient availability and quality and has the potential to improve their use as a food-based strategy. It is therefore important to consider processing methods and conditions in the design of the desired edible insect product and anticipated nutrition outcome. More research on the effect of processing methods on nutrient bioavailability which includes the influencing mechanism is required. Furthermore, research is required to provide empirical evidence on nutritional outcomes and confirm the nutritional benefits by developing edible insect-based products, investigating bioavailability *in vitro* and *in vivo* and conducting more rigorous clinical trials. More rigor in design and execution, and extensive human trials on the nutritional benefits and other health promoting properties could also allow evidence on the impact of specific insect species on certain aspects of human health to be explored further if the health benefits are to be clarified. Moreover, the sustainability of insects needs to be considered with rearing, legislation, food safety and ethical issues being addressed.

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Data availability statement

Data availability is not applicable to this article as no new data were created or analysed in this study.

Ethical approval

Ethical approval was not required for this research.

Conflicts of interest

The authors declare that they have no conflict of interests.

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Table 1: Summary of studies showing the effect of edible insect-based foods on nutrition status.

Article	Type of study	Insect	Form of edible insect	Quantity of insects	Subjects/age group	Sample size	Study duration	Country	Targeted nutrition outcomes	Findings
Omollo (2014) (*Thesis*)	Randomized, double- blind trial	Termites (*Macrotermes* subhylanus)	Complementary foods (WinFood Classic)	10% termites	Infants (6 months)	499	9 months	Kenya	Lean mass accrual essential fatty acid status and gross motor milestone attainment	No significant differences in essential fatty acid profile, lean mass accrual and gross motor milestone attainment.
Bauserman et al. (2015a) (*Scientific paper)*	Cluster randomized trial	Caterpillars	Cereal	-	Infants (6 months)	175	12 months	Democratic Republic of Congo	Stunting, anemia	No reduction in the prevalence of stunting. Higher hemoglobin concentration with fewer anemic cases.
Skau et al. (2015) (*Scientific paper)*	Single blind randomized community-based trial	Edible spiders (*Haplopelma* species)	Rice-based complimentary food products	1.8 % edible spiders	Infants (6 months)	419	9 months	Cambodia	Height, weight, body composition assessed by fat free mass, fat mass.	No difference was found.
Homann (2015) (*Thesis*)	Randomized parallel study	Crickets	Biscuits	10% cricket powder	Children (5-10 years)	54	Four weeks	Kenya	Gut microbiota, Body weight	There was no difference in gut microbiota as well as percent change in weight and BAZ (BMI-for-age z-score).
Stull et al. (2018) (*Scientific paper)*	Double-blind, crossover trial	Crickets	Breakfast shakes	25g/day	Adults (18-65)	20	Six weeks	Colorado	Gut health-microbiota changes, liver function	Cricket consumption tolerable and non-toxic at the studied dose (25mg/day). Cricket powder consumption was associated with reduced plasma TNF-α and

										supported growth of *Bifidobacterium animalis*, which increased 5.7-fold.
Konyole et al. (2019) (*Scientific paper)*	Randomized, double- blind trial	Termites (*Macrotermes* subhylanus)	Complementary foods (WinFood Classic)	10% termites	Infants (6 months)	499	9 months	Kenya	Primary outcomes- Fat-free mass (FFM), length, plasma ferritin, plasma transferrin receptors, and hemoglobin Secondary outcomes- weight, MUAC, head circumference and skinfolds	No differences in FFM gain and length in the insect-based trial group compared to the other 2 non-insect-based food trial groups. Weight gained in all 3 groups was mainly FFM whereas FM remained unchanged. Decrease in plasma ferritin. Increase in plasma transferrin receptors. Reduction in hemoglobin and anemic prevalence was slightly higher. Poor iron status indicators attributed to the inhibitory effect of amaranth which was a main ingredient in the two meals.
Kipkoech (2019) (*Thesis*)	Single-blind randomized controlled dietary intervention	Cricket (*Acheta domesticus*)	Porridge	5% cricket powder per serving	Children (3-4.5 years)	138	6 months	Kenya	Hemoglobin, fatty acid levels, weight	Improved anthropometric indices and significant difference in fatty acid and hemoglobin levels.

Table 2: Effect of processing on the bioavailability of nutrients in edible insects and edible-insects based products

Article	Insect	Product type	Processing method	Nutrients	Impact on nutrients
Manditsera et al. (2019) *(scientific paper)*	*Eulepida mashona* (beetle)	Whole insect	Boiling, Boiling twice, Roasting,	Zinc and iron	No effect on zinc and iron content Boiling caused a reduction in bioaccessibility of zinc and iron. Roasting had no effect on bioaccessible zinc and iron. Significant decrease in protein content and digestibility after boiling for 60 min and twice.
				Protein	Roasting only had no impact on both protein content and digestibility.
Manditsera et al. (2019) *(scientific paper)*	*Henicus whellani* (cricket)	Whole insect	Boiling Roasting,	Zinc and iron	Both methods had no effect on zinc and iron content and bioaccessibility of iron.
				Protein	Boiling caused a significant decrease in protein content. Boiling and roasting caused a reduction in protein digestibility.
Madibela et al. (2007) *(scientific paper)*	*Gonibrasia belina* (Mopane worm)	Whole insect	Degutting Boiling, Hot ash roasting	Zinc Protein	Degutting caused a higher concentration of protein and the in vitro true dry matter digestibility. Decrease in both zinc and protein content. Decrease in the in vitro true dry matter digestibility
Megido et al. (2018)	*Tenebrio molitor* L.	Whole insect	Boiling, Vacuum	Protein	Frying only caused a significant decrease in protein content.

(scientific paper)	(mealworm)		cooking Frying Oven cooking (15 and 30 min)		All other methods except frying caused a significant increase in vitro crude protein digestibility.
Lautenschlager et al. (2017) *(scientific paper)*	*Imbrasia epimethea* (edible caterpillar)	Whole insect	Evisceration (degutting) Boiling Drying	Protein	Evisceration caused a significant increase in protein content Boiling only and boiling and drying had no significant impact on the protein content.
Babiker (2008) *(scientific paper)*	*Anacridium melanorhodon* (Sudanese tree locusts)	Flour	Boiling Frying	Zinc and iron Protein	Zinc and iron contents and extractability higher in the flour from the boiled than the fried tree locust Rich in protein Frying significantly reduced the in vitro protein digestibility.
Kinyuru et al. (2010) *(scientific paper)*	*Macrotermes subhylanus* (Termite)	Whole insect	Fresh dried Toasting Toasted-dried	Protein	No significant effect on in vitro digestibility
Kinyuru et al. (2010) *(scientific paper)*	*Ruspolia differens* (Green and brown grasshopper)	Whole insect	Fresh dried Toasting Toasted-dried	Protein	Decrease in the in vitro digestibility
Poelaert et al. (2016) *(scientific paper)*	*Acheta domesticus* (adult house	Whole insect	Autoclaved Oven cooked	Protein	No impact on crude protein content In vitro crude protein digestibility significantly reduced

	crickets)				
Poelaert et al. (2016) *(scientific paper)*	*Tenebrio molitor* (mealworm larvae)	Whole insect	Autoclaved Oven cooked	Protein	No impact on crude protein content In vitro crude protein digestibility significantly reduced
Cho et al. (2018) (*scientific paper*)	*Tenebrio molitor* (mealworm larvae)	Insect sauce	Fermentation	Amino acid	Increase in amino acid composition and amino acid derivatives
Cho et al. (2019) (*scientific paper*)	*Bombyx mori* (silkworm)	Whole insect	Fermentation	Amino acid Zinc and iron	Decrease in the total free amino acid amounts Zinc and iron contents reduced
Mendoza-Salazar et al. (2021) (*scientific paper*)	*Tenebrio molitor* (mealworm) *Sphenarium purpurascens* (grasshopper)	Flour	Fermentation	Protein content	Increase in the protein content Increase in the peptide profile

Figures

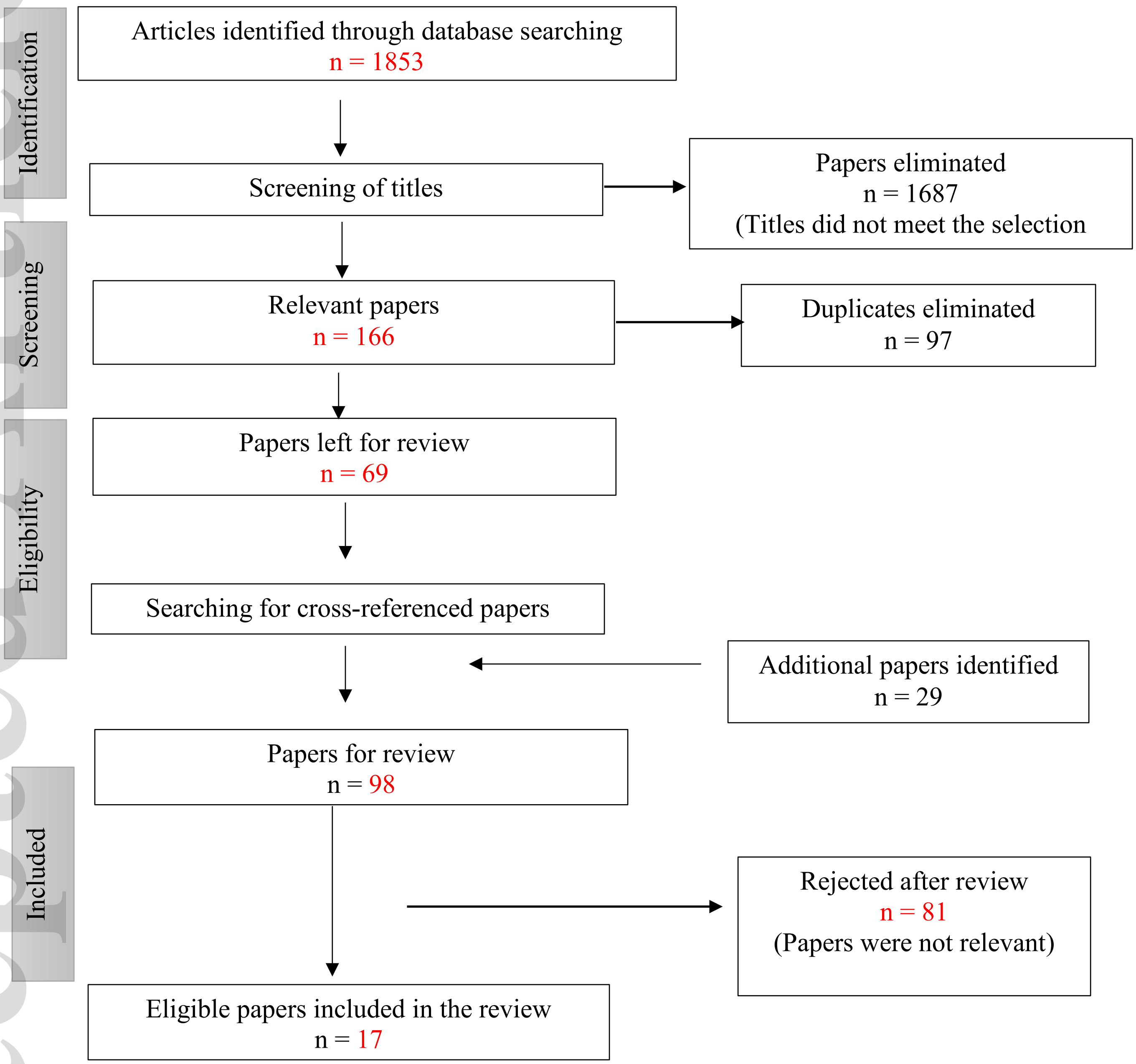

Figure 1

Figure captions

Figure 1: Literature Search Strategy