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REVIEW ARTICLE

Positioning earthworms in the future foods debate: a systematic review of earthworm nutritional composition in comparison to edible insects

E. Sonntag[1,2,3*], *A. Vidal*[3], *D. Grimm*[1,4], *G. Rahmann*[1,4], *J.W. van Groenigen*[3], *H. van Zanten*[2] and *A. Parodi*[2]

[1]Thuenen Institute of Organic Farming, Trenthorst 32, 23847 Westerau, Germany; [2]Farming Systems Ecology Group, Department of Plant Sciences, Wageningen University & Research, P.O. Box 9101, 6700 HB Wageningen, the Netherlands; [3]Soil Biology Group, Department of Environmental Sciences, Wageningen University & Research, P.O. Box 430, 6700 AK Wageningen, the Netherlands; [4]University of Kassel, Steinstrasse 19, 37213 Witzenhausen, Germany; *enno.sonntag@thuenen.de

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Abstract

Sustainable food system innovations are urgently needed to feed a growing human population while staying within planetary boundaries. Farmed edible insects have received considerable scientific and public attention due to their potential to improve food system circularity by upcycling nutrients from organic residual streams to nutritious food. Earthworms, as non-insect invertebrates, have remained largely unrecognized in the future foods debate. However, they are already widely farmed at industrial scale for their capacity to recycle organic wastes and improve soil fertility. We conducted a systematic literature review to provide a quantitative basis on earthworm nutritional composition, thereby positioning earthworms in the future foods debate. Here we show, based on evidence from 142 scientific studies, that farmed earthworms are a potentially interesting food source. They have an attractive nutrient composition compared to the main farmed edible insect species, being especially rich in protein, low in fat and containing a favourable profile of essential amino acids. The content of important fatty acids, minerals and vitamins in earthworm biomass is higher or lower than in edible insects, depending on the feed material. Crude protein and fat contents are higher in farmed versus wild earthworms, indicating that farming conditions provide a lever for further improving the nutritional composition of earthworm biomass. Whether earthworm species or feed materials affect earthworm nutritional composition could not be finally clarified based on the available data. We conclude that earthworms have high potential as a future food from a nutritional perspective, mainly as an alternative source of protein. The integration of earthworm farming in future food systems can be expected to improve sustainability and circularity, potentially giving earthworms an advantage over edible insects.

Keywords

vermiculture – protein – amino acid – fatty acid – proximate composition

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1 Introduction

The global population and thereby the demand for food continue to grow (United Nations, 2022), while current food production systems are increasingly jeopardized by environmental degradation (Mirzabaev *et al.*, 2023). Food production, especially animal husbandry, is also a major driver of environmental degradation and greenhouse gas emissions (Pelletier and Tyedmers, 2010). Future food systems will therefore need to combine a reduction of environmental impact with increased resilience to weather extremes and sufficient production of healthy food (Willett *et al.*, 2019; Herrero *et al.*, 2020). Future foods, such as edible insects, algae, or fungi, have been proposed as nutritious and sustainable alternatives to conventional animal-derived foods that have a high environmental impact (Grimm and Wösten, 2018; Parodi *et al.*, 2018; Ullmann and Grimm, 2021). Future foods are defined as scalable technologies that facilitate high productivity within controlled conditions, require minimal space, and consequently hold potential to reduce land-use and greenhouse gas emissions (Parodi *et al.*, 2018; Mazac *et al.*, 2022).

Besides being environmentally sustainable, future foods also need to provide sufficient nutrients for a healthy diet. The nutritional quality of future foods, as of any other food, can be evaluated based on their proximate composition, which includes moisture, ash, lipid, protein and fibre contents (Thangaraj, 2016). Nutritional quality is further defined by the content of specific organic compounds, such as amino and fatty acids. Amino acids are the building blocks of protein (Hambræus, 2014). The essential amino acids are of special importance, as they cannot be synthesized by the human body and need to be taken up with food (World Health Organization, 2007). The same applies to the essential unsaturated fatty acids cis-linoleic acid (LA, 18:2) and α-linolenic acid (ALA, 18:3) (Das, 2006). Their metabolic successors arachidonic acid (ARA, 20:4), eicosapentaenoic acid (EPA, 20:5) and docosahexaenoic acid (DHA, 22:6) can be synthesized in the human body, but are also an important component of healthy diets (Kaur *et al.*, 2014). Further important nutrients are minerals and vitamins, where deficiencies are common in calcium, iodine, iron and zinc and the vitamins A, folic acid and cobalamin (B_{12}) (Sanghvi *et al.*, 2007; Harinarayan *et al.*, 2021).

Insect farming has received considerable scientific and public attention in the future foods debate but important drawbacks have remained unattended. Insects are rich in protein and contain a complete fatty acid profile (Finke, 2002). In the European Union four species are currently approved for commercialisation as food under the Novel Foods Legislation (Regulation (EU) 2015/2283, 2015), and others are under evaluation. Commonly farmed insects, such as black soldier fly larvae (*Hermetia illucens*, Linnaeus 1758), house crickets (*Acheta domesticus*, Linnaeus 1758), and yellow mealworms (*Tenbrio molitor*, Linnaeus 1758) can be fully or partially fed with organic residual streams, and hence allow upcycling of nutrients to protein-rich food or feed (van Huis, 2020). However, current practice in insect farming often deviates from this ideal due to EU Regulations, which limit the range of approved feed materials (Żuk-Gołaszewska *et al.*, 2022). As a result, high quality feeds such as cereal flour, soymeal, skimmed milk and compounded chicken feed (Makkar *et al.*, 2014; Dobermann *et al.*, 2017; Bosch *et al.*, 2020; Oonincx *et al.*, 2020) are commonly used in insect farming. This practice calls for a feed-versus-food debate and raises questions on environmental sustainability (Gianotten *et al.*, 2020; Parodi *et al.*, 2022). In addition, insect farming requires precisely controlled environmental conditions, including lighting, ventilation and particularly temperature regulation (Cortes Ortiz *et al.*, 2016). The associated energy costs of insect farms currently pose a limitation to scalability in temperate regions (Halloran *et al.*, 2016; van Huis and Oonincx, 2017). For these reasons it is interesting to also look at other invertebrates, the potential of which has so far been under-explored. In particular, less heat dependent, detrivorous invertebrates such as earthworms are potential candidates as future foods.

Earthworm farming, also referred to as vermiculture, is practiced at industrial scale since the late 1970s (Edwards *et al.*, 2011). The potential of using earthworm biomass as a protein source for human nutrition (Sun and Jiang, 2017), however, remains currently unrealized. Earthworms play a key role in nutrient cycling and soil fertility (Blouin *et al.*, 2013). In vermiculture, this capacity is utilized to recycle organic wastes and produce vermicompost, a high-quality organic fertilizer (Rehman *et al.*, 2023). Optimal culture conditions for earthworms are well established (Edwards and Dominguez, 2011; Lowe *et al.*, 2023) and employed worldwide in vermiculture systems ranging from low-tech to industrial scale (Sherman, 2018). These systems are generally based on litter-dwelling (epigeic) earthworms (Lowe *et al.*, 2023), which consume decomposing organic materials, as opposed to endogeic and anecic earthworms, which live in and primarily consume mineral soil with associated decomposed organic matter (Bouché, 1977).

Five litter-dwelling species are preferred in vermiculture due to their high reproductive rates and adaptability to variable culture conditions (Edwards and Dominguez, 2011). This includes the temperate species *Eisenia andrei* (Bouche, 1972), *Eisenia fetida* (Savigny, 1826), and *Dendrobaena veneta* (Rosa, 1886), and the tropical species *Eudrilus eugeniae* (Kinberg, 1866), and *Perionyx excavatus* (Perrier, 1872). The biomass of farmed earthworms can be used as a valuable protein source, as was first suggested by Lawrence and Millar in 1945. Earthworms are rich in protein and essential amino acids of comparable quality to other animal-based protein sources (Zhenjun *et al.*, 1997; Sun and Jiang, 2017), and a good source of minerals and vitamins (Domínguez *et al.*, 2017). Not surprisingly, earthworms are traditionally appreciated as food by diverse cultures around the world (Paoletti *et al.*, 2003; Grdiša *et al.*, 2013; Ding *et al.*, 2019) and recognised as a suitable fish-meal replacement in poultry or aquaculture feeds (Parolini *et al.*, 2020). While various authors have analysed the nutritional composition of earthworms and indicated their potential as human food (Sabine, 1983; Zhenjun *et al.*, 1997; Sun and Jiang, 2017), a comprehensive overview is currently lacking and earthworms remain largely unrecognized in the ongoing debate on future foods.

The primary aim of this article is to establish a quantitative basis for the nutritional quality of earthworms, thereby positioning earthworms in the future foods debate. The research objectives were (1) to compare the nutritional composition of wild and farmed earthworms, highlighting potential effects of cultivation, (2) to investigate the effect of species and feed sources on earthworm nutritional composition, and (3) to compare the nutritional quality of earthworms with three species of commonly farmed edible insects. To this end, we conducted a structured literature review of scientific publications on earthworm nutritional characteristics.

2 Methodology

2.1 *Literature search strategy*

The present review was performed according to the PRISMA guidelines (Page *et al.*, 2021) and followed a two-round search process (Figure 1). We first searched scientific databases for publications of earthworm nutritional data (Round 1), and then searched for further references in those articles (Round 2), which were eligible based on predefined screening criteria. The search terms used in the first step were pilot tested in advance to ensure high relevance of search results. We performed the final database search on 9th March 2023 in Scopus and Web of Science including titles, abstracts and keywords and using the following search phrase:

"earthworm" AND ("food" OR "feed") AND ("chemical composition" OR "protein")

Duplicates and one erratum were removed from the search results before screening.

2.2 *Screening: inclusion and exclusion criteria*

The results of the database search (Round 1) were screened by title and abstract and sought for retrieval if they appeared to provide earthworm nutritional data. Retrieved reports were then assessed by the first author for eligibility and included in the review if they met the following criteria: (1) published as an original research article, book chapter, government report, workshop or conference proceedings, (2) written in a language read by the authors (English, German, Spanish) or containing data in a readable table, (3) provides data on nutritional characteristics of earthworms, including proximate composition, essential amino acids, fatty acids, minerals, and vitamins, (4) review articles, if original source could not be obtained. The exclusion criteria were: (1) does not provide relevant earthworm nutritional data, (2) review articles using non-original data, (3) data identical to a previous publication, (4) newspaper articles and PowerPoint presentations, (5) data contained errors. Eligible studies and excluded reviews were then used for citation searching (Round 2). Studies identified in the second round were submitted to the same screening process.

2.3 *Data extraction and standardization*

The 142 articles accepted for review were listed in a table (Supplementary Table S1), including title, authors, journal and year of publication. One reviewer then extracted the available earthworm nutritional data with corresponding units, including proximate composition, essential amino acids, fatty acids, minerals, and vitamins, to the table. In addition, one reviewer extracted information regarding the earthworm species, feed material, gut voiding, drying method and analysed material (fresh earthworms/earthworm meal).

The nutritional data was then standardized by one of the reviewers to ensure comparability and double checked by another reviewer. Dry matter (DM) and water content of fresh earthworms were calculated to percentage of fresh matter (FM). Proximate composition, essential amino acids, minerals and vitamins were calculated to % DM, if the water content was given and excluded from the dataset otherwise. Where total

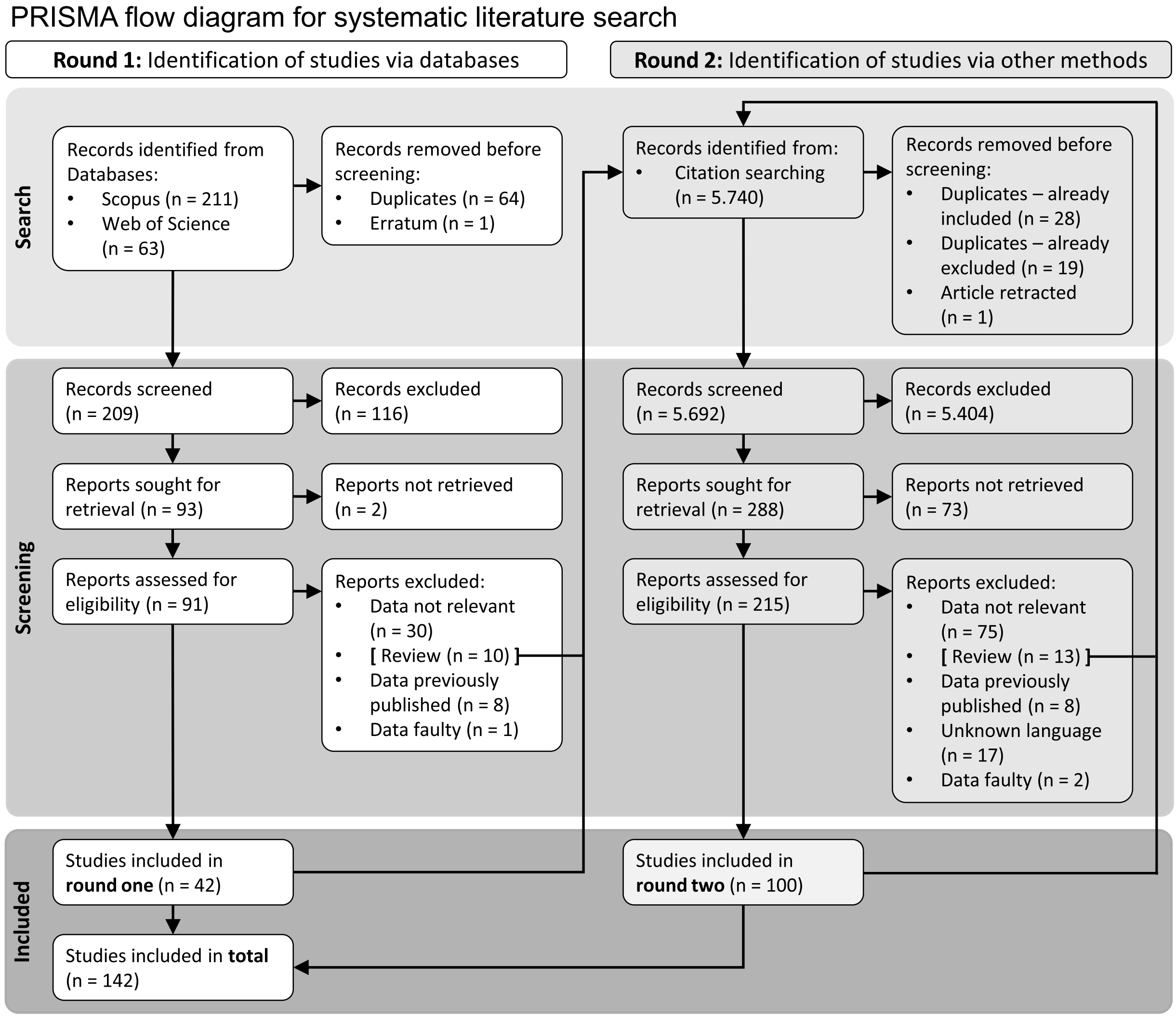

FIGURE 1 PRISMA 2020 flow diagram showing the systematic two-step search process used to identify literature for the present review. In round one (left side), literature was identified via databases, and in round two (right side), literature was identified via citation searching.

nitrogen but not crude protein was given in an article, we used the conversion factor of 6.25 to calculated crude protein. In some cases, tables or data were poorly labelled. A recurring example was the use of the term dry weight where earthworm meal containing around 9% moisture was analysed. In such cases we corrected the unit to wet weight, based on comparison with data from other articles. This approach was chosen to maintain a sufficient number of datapoints for our review, assuming that the analysis was done correctly and only the data described poorly in the concerned studies. Fatty acids were kept as % total fatty acids, because crude fat and water content of the original sample were often omitted in the respective articles. Data was excluded from the analyses if standardization was not possible due to missing information (e.g. water content), or if part of the data was erroneous (e.g. proximate composition > 100%). Earthworm species names were updated using DriloBASE (Drilobase Project, 2013) where possible.

For reference, we added data for three species of commonly farmed edible insects to Figure 2 and Figure 5. These species are house crickets, black soldier fly larvae, and yellow mealworms. Means and ranges for proximate composition were taken from recent reviews (Gkinali *et al.*, 2022), or calculated from data given in, or as supplementary to a review (Lu *et al.*, 2022; Ververis *et al.*, 2022). Insect fatty acid data in Table 1 were gathered from Paul *et al.* (2017), and Oonincx *et al.* (2020). Values for essential amino acids in Figure 5 were either taken from recent reviews (Hong *et al.*, 2020; Lu *et al.*, 2022), or, in the case of house cricket, calculated from two individual studies (Finke, 2002; Udomsil *et al.*, 2019). Data for mineral and vitamin content for edible insects in

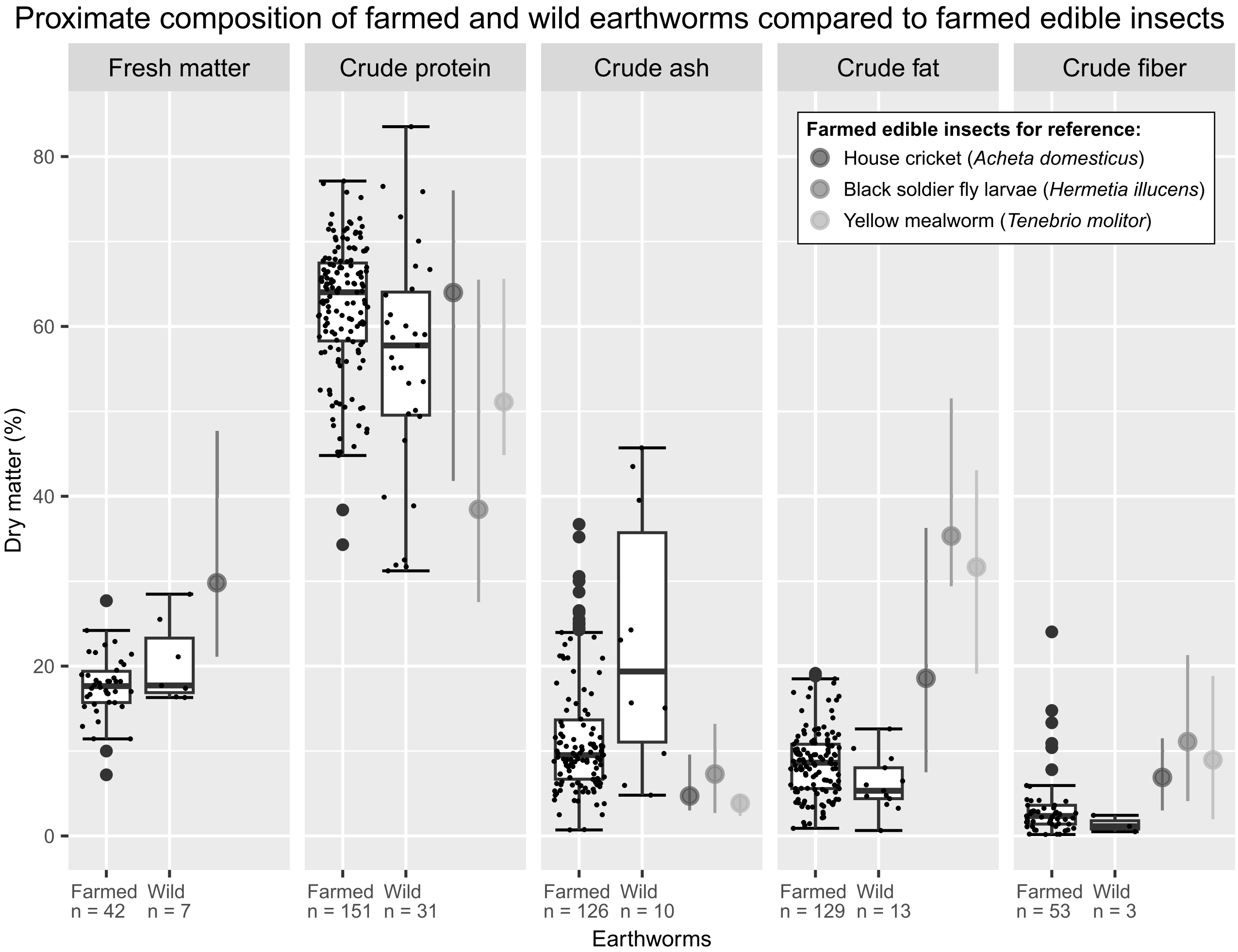

FIGURE 2 Boxplots show the proximate composition of farmed and wild earthworms in comparison with three species of commonly farmed edible insects, which are indicated as point-ranges. Dots outside of boxplots are outliers and points in the point-ranges indicate the mean. The dry matter content is given as percentage of fresh matter, and all other nutrients are given as percentage of total dry matter. Earthworm data was compiled by the authors from individual studies and data for edible insects taken from recent reviews (Gkinali *et al.*, 2022, Lu *et al.*, 2022, Ververis *et al.*, 2022). The number of datapoints were as follows: house cricket: n = 25, 36, 31, 35, 16, respectively for each component in the order of the figure; black soldier fly larvae: n = 0, 6, 6, 6, 3; yellow mealworm: n = 0, 13, 11, 12, 8.

Tables 2 and 3, respectively, were taken from individual studies (Pennino *et al.*, 1991; Finke, 2002, 2007, 2013; Zielińska *et al.*, 2015; Latunde-Dada *et al.*, 2016; Shumo *et al.*; Chia *et al.*, 2020; Sikora *et al.*, 2023).

2.4 *Search results*

As Figure 1 shows, a total of 274 records was found in the data base search (Scopus: 211, Web of Science: 63), including 64 duplicates. After screening by title and abstract, 93 reports were retrieved for full-text review, of which 49 were excluded for the following reasons: no earthworm nutritional data was provided (n = 30), reviews of non-original data (n = 10), data identical to previously published article (n = 8), data contained errors (n = 1). In this first round, 42 publications were accepted for review. In round two, we excluded one retracted article, and those already found and in- or excluded in the previous search (Round 1), and then screened 5,692 records by title. Of these, 288 were sought for retrieval as potential sources of earthworm nutritional data. We gathered 217 reports via publishers, websites or libraries of which 115 were excluded for the following reasons: no earthworm nutritional data was provided (n = 75), review of non-original data (n = 13), data identical to previously published article (n = 8), language not spoken by the authors (n = 17), data contained errors (n = 2). Finally, 100 studies were accepted in round two, adding up to a total of 142 included studies.

Of the 142 included studies, 133 provided full or partial data on proximate composition, 60 analysed essential amino acids, 39 minerals, 24 fatty acids, and seven

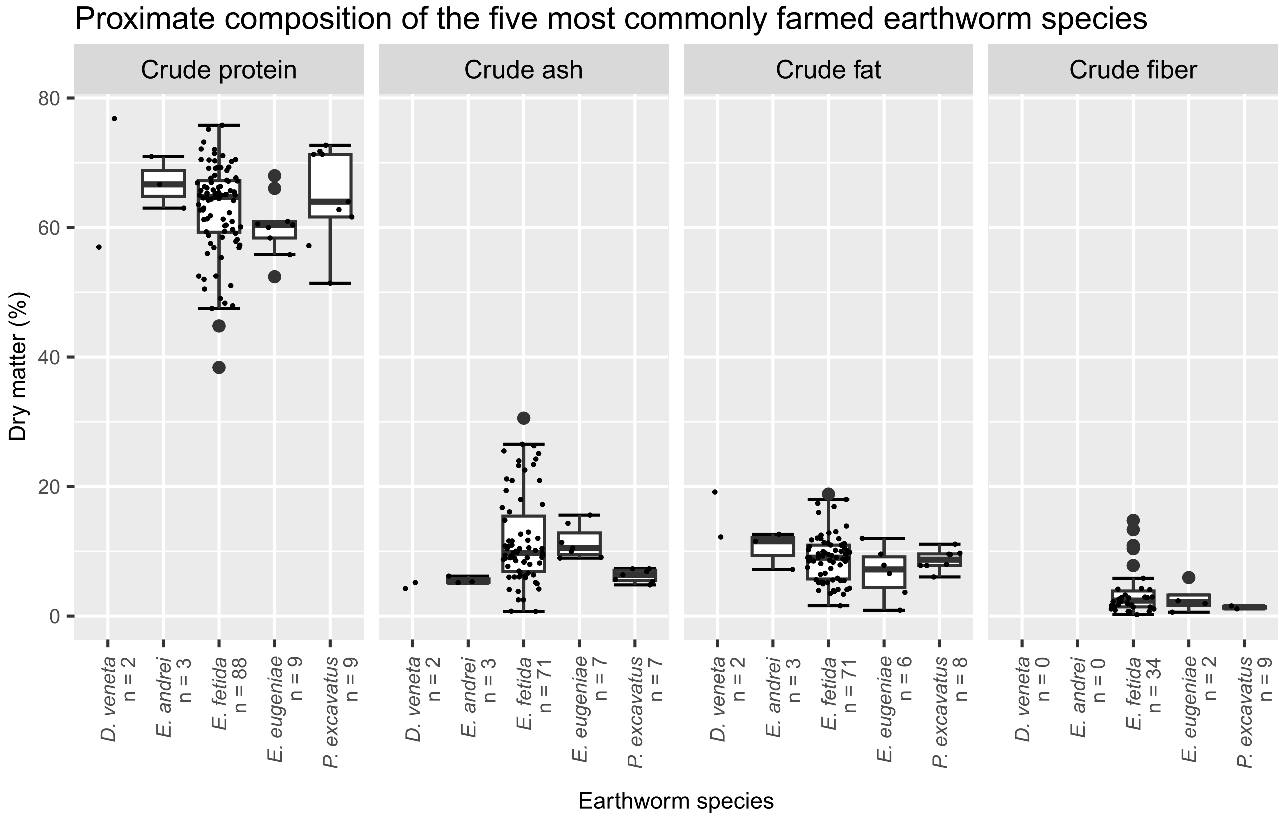

FIGURE 3 Boxplots show the proximate composition of the five most commonly farmed earthworm species *Dendrobaena veneta*, *Eisenia andrei*, textitEisenia fetida, *Eudrilus eugeniae*, and *Perionix excavatus*. Larger dots indicate outliers. In *D. veneta* less than three datapoints were available, which are shown as small dots without boxplot.

vitamins. We found data on a total of 25 distinct earthworm species and two two-species combinations.

3 Farmed vs wild earthworms

Figure 2 shows the proximate composition of 10 farmed and 16 wild earthworm species compared to three species of commonly farmed edible insects, which are included as a reference. Live earthworms contain on average 18% dry matter (DM), which is predominantly composed of protein, followed by ash, fat and fibre.

We observe notable differences between the nutritional composition of farmed and wild earthworms (Figure 2), which are likely linked to differences in habitat, feed material and post-harvest handling. Farmed earthworms have on average higher crude protein, fat and fibre contents, while their ash content is lower than in wild earthworms. Earthworms can be classified according to their habitat and diet preferences (Bouché, 1971). In our data-set, 83.3% of farmed earthworms are litter-dwellers, while this is only the case for 35.3% of the wild earthworms. Accordingly, the majority of the wild earthworms are soil-dwellers, which can be expected to have more mineral particles in their gut than litter-dwelling species. Furthermore, farmed earthworms are usually fed with energy- and nitrogen-rich organic materials including manure, fruit and vegetable waste, or kitchen waste (Sherman, 2018), while wild earthworms typically consume feed of lower quality. Hence, better nitrogen and energy availability in the feed and less energy expenditure may contribute to higher protein and fat contents observed in farmed earthworms. Similarly, this has been observed for fat contents in farmed compared to wild insects (Oonincx and Finke, 2021). We found no difference in essential amino acid composition between farmed and wild earthworms.

The high variability of crude ash content in farmed and wild earthworms and the prevalence of outliers in farmed earthworms, are likely artefacts of methodological inconsistency in post-harvest handling. Only one third (n = 47) of the analysed studies report treatment to void the earthworms' gut prior to analysis, and for varying periods of time (0.5–48 h). As a result, high ash and fibre contents observable in some studies negatively distort overall earthworm protein and fat contents. In summary, the use of feed materials with low mineral content and consistent voiding of the gut after harvest-

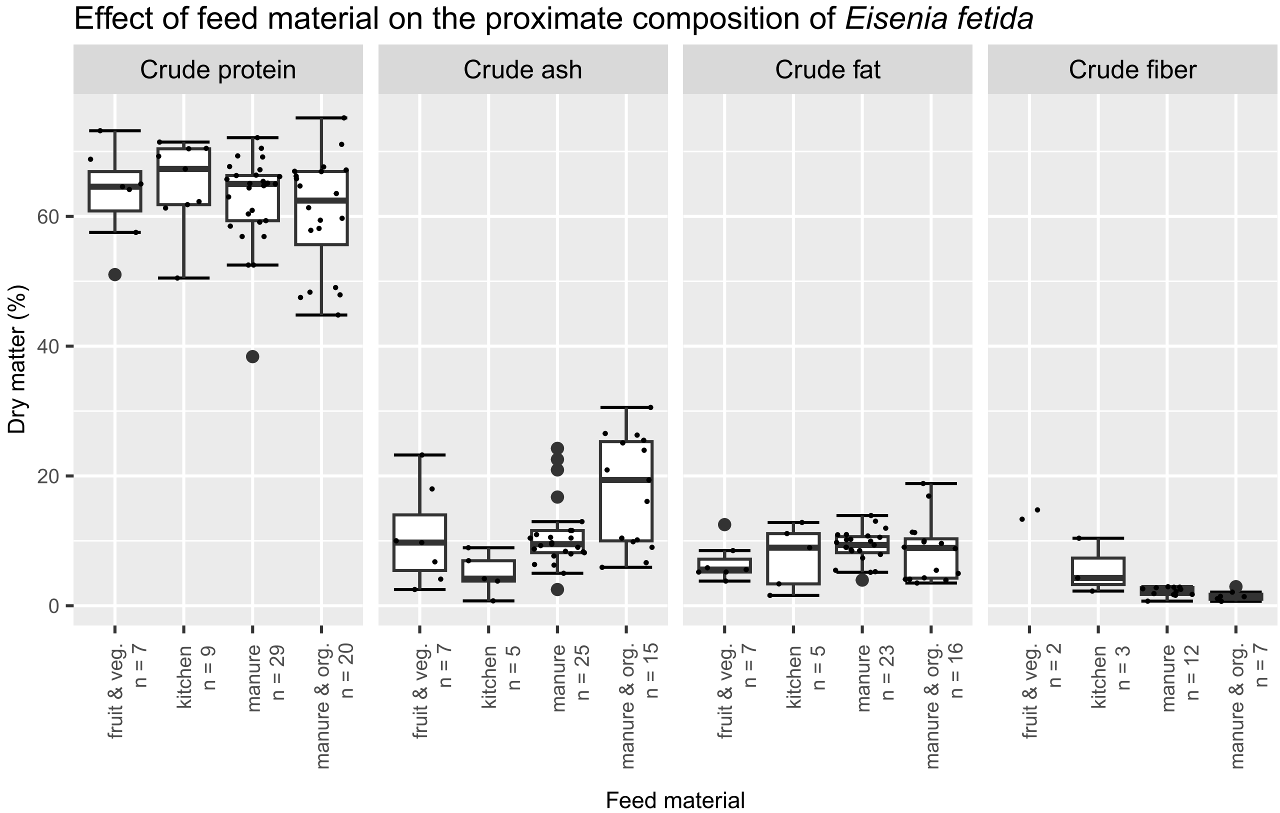

FIGURE 4 Boxplots show the proximate composition of *Eisenia fetida* farmed on the following feed materials: fruit and vegetable waste, kitchen waste, manure, and a mix of manure and organic waste. If less than three datapoints were available, they are indicated as small dots without boxplot. Larger dots indicate outliers.

ing of earthworms provide levers for improving their nutritional composition.

4 Commonly farmed earthworm species

The nutritional composition of the five most commonly farmed earthworm species (Edwards and Dominguez, 2011) is shown in Figure 3. *E. fetida* is by far the most abundant species in our dataset (n_{total} = 107, n_{farmed} = 88), reflecting its ubiquitous use in vermiculture. It is followed by *E. eugeniae* (n_{total} = 15, n_{farmed} = 9) and *P. excavatus* (n_{total} = 12, n_{farmed} = 9), while *D. veneta* and *E. andrei* are underrepresented in our dataset compared to their use in commercial vermiculture.

From the available data, it appears that nutritional differences between commonly farmed earthworm species are small. However, it is difficult to disentangle the effects of species, feed material, and vermiculture conditions given the few available datapoints for most species. Direct comparisons of several earthworm species in controlled feeding experiments are rare in the literature. Nonetheless, the studies we found indicate that protein content may vary up to 14% between species farmed under the same conditions (Tacon *et al.*, 1983; Reinecke *et al.*, 1991b; Kumar *et al.*, 2022). Further investigation of this topic may help to select particularly nutritious earthworm species for human consumption. Certain earthworm species may also be preferable to others in terms of flavour (Cayot *et al.*, 2009).

5 Eisenia fetida – a versatile eater

The most extensively farmed earthworm species, *E. fetida*, demonstrates adaptability to a wide range of feed materials without compromising its average protein content (Figure 4). However, there is considerable variation of up to 20% DM within the feed categories, showing that certain feeds, probably containing more ash, reduce the protein content. The effect of diet may be more pronounced in other, less adaptable earthworm species. Studies investigating this topic are extremely rare and do not reach consistent conclusions. García *et al.* (2009) found variations of crude protein content in *Eisenia spp*. of up to 7% DM, which is notable considering the small differences in the feed mixes used by the authors. While diet appears to have limited effects on

TABLE 1 Content of essential and other important fatty acids in earthworms and three species of commonly farmed edible insects given as the percentage of total fatty acids

Data from:			Present review				Oonincx *et al.*, 2020		Paul *et al.*, 2017
			earthworms				black soldier fly larvae	house cricket	yellow mealworm
Fatty acid			n	mean	min	max	n = 6	n = 6	n = 3
LA	Cis-linoleic acid	C 18:2	29	7.75	0.51	39.15	9.10[c]	28.70[b]	22.83[b]
ALA	α-linolenic acid	C 18:3	5	3.89	0.64	12.22	0.50[a]	0.80[a]	0.11[a]
ARA	Arachidonic acid	C 20:4	26	11.00	0.15	19.00			0.00[a]
EPA	Eicosapentaenoic acid	C 20:5	24	13.54	1.75	20.68			
DHA	Docosahexaenoic acid	C 22:6	6	0.89	0.07	2.20			

[a] fatty acid content is on average higher in earthworms; [b] fatty acid content is on average lower in earthworms; [c] fatty acid content is comparable to earthworms.

the nutritional composition of *E. fetida*, it is known as a key factor for productivity in vermiculture (Edwards *et al.*, 2011; Sherman, 2018). Further studies should investigate the feed preferences of commonly farmed earthworm species so that they can transform organic residual streams to edible protein most efficiently.

6 Higher in protein and lower in fat – earthworms vs edible insects

The crude protein content in farmed earthworms is at least as high and variable as in farmed edible insects (Figure 2), with average values of 62.3% DM and 63.9% DM for farmed earthworms and house crickets, respectively. It has to be noted that the protein content of insects has often been overestimated due to non-protein nitrogen present in the form of uric acid, β-alanine, and chitin exoskeletons (Janssen *et al.*, 2017; Hopkins *et al.*, 2021; Oonincx and Finke, 2021). Chitin content also varies across insect species and life stages (Oonincx and Finke, 2021) and the use of adjusted nitrogen-to-protein conversion factors (K_p) has been suggested accordingly (Janssen *et al.*, 2017). In the present review, 45 out of 60 studies used as references for insect protein content in Figure 2 applied the conventional K_p of 6.25 and therefore likely overestimated insect protein content. When corrected K_p of 4.43, 5.41 and 5.09 are used for black solder fly larvae (Smets *et al.*, 2021), yellow mealworm (Boulos *et al.*, 2020), and house crickets (Ritvanen *et al.*, 2020), respectively, the actual insect protein content is reduced by 11.2%, 6.9%, and 11.9%, respectively. After such corrections, it becomes clear that farmed earthworms exceed important farmed insects in mean protein content. In earthworms, chitin is present in the gizzard epithelium (Peters and Walldorf, 1986), which is only 10-50 μm thick in *L. rubellus* (Yaqub, 1997b) and therefore is negligible in this context.

Earthworm fat content, with an average value of 8.6% DM, is half the value or lower than in farmed edible insects. The fatty acid composition of farmed earthworms was analysed by 14 studies in our dataset and results are summarized in Table 1. The reported variation of individual fatty acids may be related to fatty acid content of feed materials (Dynes, 2003a), but also differs seasonally and by species (Petersen and Holmstrup, 2000b; Holmstrup *et al.*, 2007). The essential LA, and important ARA and EPA are present in earthworms at approximately 0.7, 1.0 and 1.2% of total dry matter, respectively. The proportion of ALA in the total fatty acids of earthworms is higher than in black soldier fly larvae, house crickets and yellow mealworms, while the proportion of LA is comparable to black soldier fly larvae, and lower than in house crickets and yellow mealworms (Paul *et al.*, 2017; Oonincx *et al.*, 2020). Fat content and fatty acid composition in insects are strongly influenced by feed material but also depend on species, life stage and environmental factors (Oonincx *et al.*, 2020; Oonincx and Finke, 2021). The influence of feed material on the fatty acid composition of earthworms requires further investigation. Essential and other important fatty acids in earthworms may provide additional nutritional benefits, yet earthworms should be viewed primarily as a source of protein with a low fat content.

The crude ash content in farmed earthworms, with a mean of 11.7% DM, is slightly higher than that in farmed edible insects, of which black soldier fly larvae have the highest content with 8.2% DM. A potential explanation is that, although not strictly necessary, soil is often added to the substrate in vermiculture containers, thus increasing the amount of mineral particles in the earthworm gut. In addition, these mineral particles were not consistently voided from the earthworm gut in several studies and thus included in the analysis.

The crude fibre content of earthworms, with a mean of 3.5% DM, appears to be slightly lower compared to edible insects, where the lowest value is found in house crickets with 7.3% DM. The fibre fraction of earthworms and insects is not well studied. Fibre in insects is known to contain proteins, sclerotised proteins, minerals and other substances bound to chitin (Finke, 2007; Oonincx and Finke, 2021).

7 The favourable amino acid profile of earthworms

Earthworm protein contains a complete profile of essential amino acids (EAA) similar to that of edible insects (Figure 5). The most abundant EAA in earthworms are leucine and lysine, with means of 5.11 and 4.15 g/100 g DM respectively, while cystine, tryptophan, methionine and histidine are present in limited amounts, with means of 0.78, 0.84, 1.17 and 1.78 g/100 g DM, respectively. When compared to whole egg, which has been used as a standard for a high-quality EAA composition (Layman and Rodriguez, 2009), it is notable that earthworms contain larger amounts of all EAA per 100 g dry matter (United States Department of Agriculture, 2019). The essential amino acids lysine, threonine, cysteine, methionine and tryptophan, which are commonly limiting in imbalanced human diets (Hambræus, 2014), are 3.8, 3.5, 1.5, 2.1 and 3.8 times higher, respectively in earthworms than in whole egg. Thus, we emphasize that earthworms hold significant potential for addressing amino acid deficiencies in imbalanced human diets.

8 Minerals and vitamins in earthworms

Earthworms could also be an interesting source of minerals and vitamins (Domínguez *et al.*, 2017). The mineral content of earthworms and three species of commonly farmed edible insects is shown in Table 2. The reported variation in earthworms is likely linked to the mineral content of different feed materials (Oonincx and Finke, 2021), although this effect may be more pronounced for some minerals (García *et al.*, 2009). Heavy metals, for instance, are known to be accumulated in earthworm body tissue to varying degrees depending on the species, metal and concentration in feed material (Ireland, 1979; Hartenstein *et al.*, 1980b; Ma, 1982; Neuhauser *et al.*, 1995; Dai *et al.*, 2004; Li *et al.*, 2010). Heavy metals of food safety concern, such as cadmium and lead, have in some cases been found to exceed permissible limits for human consumption in farmed earthworms (Graff, 1982; Hilton, 1983; Stafford, 1984; Flores and Alvira, 1987; Pereira and Gomes, 1995; Regulation (EU) 2023/915, 2023). The mineral content of edible insects, including heavy metals, is also affected by the composition of feed materials, species and stage of development (EFSA Scientific Committee, 2015; van der Fels-Klerx *et al.*, 2018; Ojha *et al.*, 2021; Oonincx and Finke, 2021). Here, we focus on the minerals calcium, iodine, iron and zinc, which are commonly deficient in human diets (Sanghvi *et al.*, 2007; Harinarayan *et al.*, 2021). The calcium content in earthworms is lower than in black soldier fly larvae (Dierenfeld and King, 2008; Finke, 2013; Chia *et al.*, 2020), and higher than in house crickets and yellow mealworms (Finke, 2002; Zielińska *et al.*, 2015; Latunde-Dada *et al.*, 2016; Köhler *et al.*, 2019; Sikora *et al.*, 2023). Iodine and iron contents are both higher in earthworms compared to the three species of edible insects and zinc contents are sometimes comparable, but may also be higher or lower in edible insects (Finke, 2007; Finke, 2013; Zielińska *et al.*, 2015; Köhler *et al.*, 2019; Chia *et al.*, 2020; Sikora *et al.*, 2023). Overall, farmed earthworms may contribute important minerals to human nutrition, if they are sufficiently present in the organic residues used as feed material and heavy metal contamination is checked.

Information on earthworm vitamin content is scarce in the literature. The available data from five studies is given in Table 3. Here we limit ourselves to the important vitamins A, folic acid and cobalamin (B_{12}), which are commonly deficient in human diets (Sanghvi *et al.*, 2007). Vitamin A can be present at higher or lower concentrations in earthworms compared to the three commonly farmed edible insects used for reference (Pennino *et al.*, 1991; Finke, 2002, 2013; Shumo *et al.*, 2019b). Folic acid is found at lower and cobalamin at higher concentrations in earthworms compared to edible insects (Finke, 2002, 2013). These findings show that earthworms may be an interesting source of vitamin A, cobalamin and other B-vitamins. Most insect species cannot synthesize B-vitamins *de novo* (Oonincx and Finke, 2021); Instead, they are absorbed from feed and the associated microbiome (Douglas, 2017; Oonincx and Finke, 2021). The common use of compound chicken feed, containing a vitamin mix, in insect rearing (Oonincx *et al.*, 2020) could explain higher contents

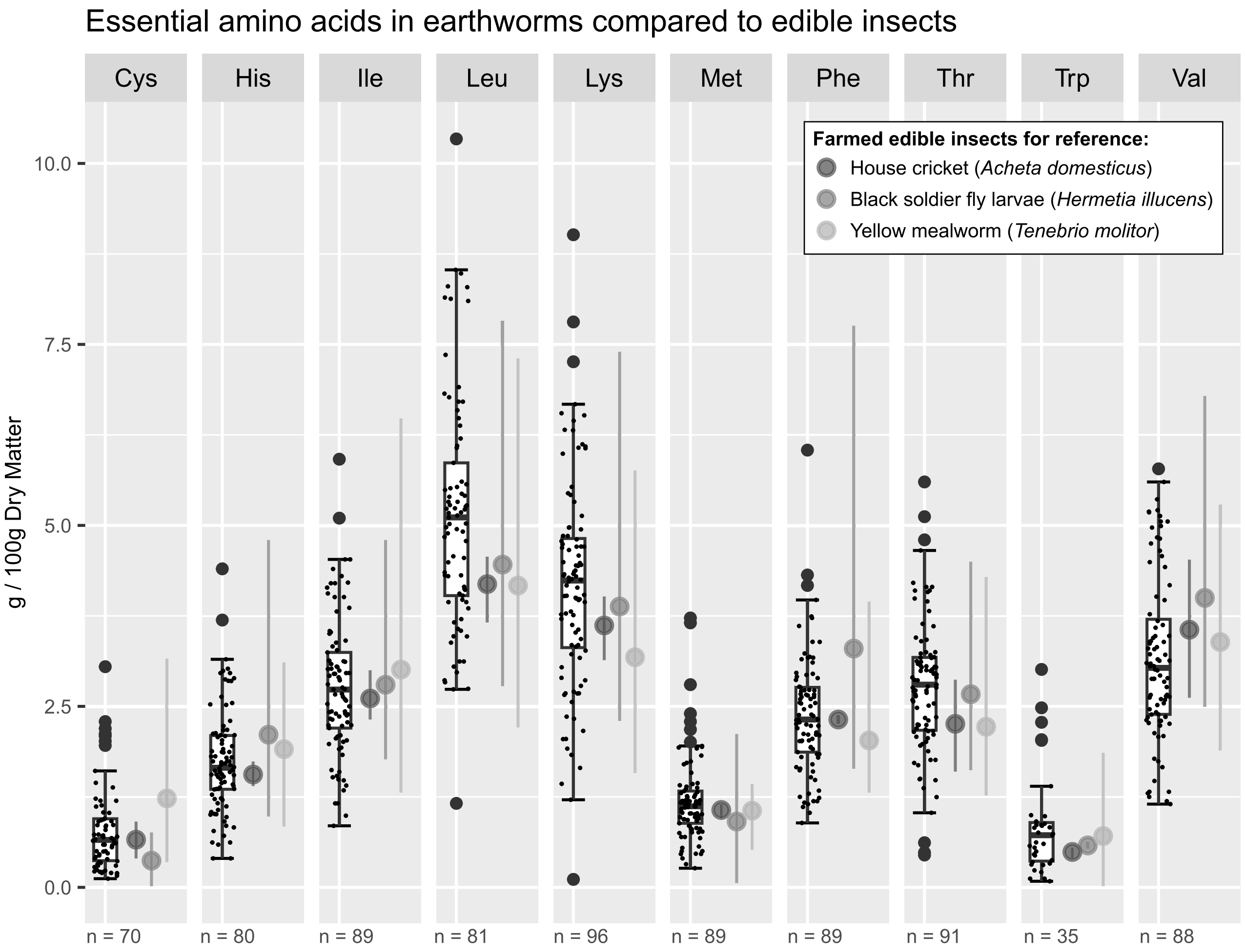

FIGURE 5 Boxplots show the content of essential amino acids in earthworms in comparison with three species of commonly farmed edible insects, indicated as point-ranges. Larger dots indicate outliers. Earthworm data was compiled by the authors from individual studies, and data for black soldier fly larvae (n = 7, 7, 7, 7, 7, 7, 7, 7, 3, 7, respectively for each amino acid in the order of the figure) and yellow mealworm (n = 6, 10, 10, 10, 10, 9, 9, 10, 4, 10) was taken from recent reviews (Hong *et al.*, 2020; Lu *et al.*, 2022), while data for house cricket (n = 2) was averaged from two individual studies (Finke, 2002; Udomsil *et al.*, 2019).

of some vitamins in edible insects. Although this has not yet been confirmed by studies, it is plausible that earthworms also acquire B-vitamins from feed and the associated microbiome. The availability of B-vitamins in earthworm feed materials may therefore become an important variable in the production of earthworms for human nutrition.

9 Earthworms in future food systems

The role of earthworms in future food systems aligns closely with that of farmed insects as they can efficiently upcycle organic residual streams into earthworm-protein for human consumption and produce vermicompost as a valuable organic fertilizer (Lowe *et al.*, 2023). Earthworm farming has three potential advantages over insect farming related to (1) energy-use, (2) the use of feed, and (3) the occurrence of diseases. First, farming earthworms, given that they are well-adapted to soil temperatures, requires less heating than farming insects outside tropical regions. Temperate and tropical earthworms tolerate temperatures of 0-35 °C and 15-35 °C, respectively, and activity in both is greatest around 25 °C (Edwards and Dominguez, 2011), while crickets and black soldier fly larvae require 30 °C and 25-30 °C, respectively (Ayieko *et al.*, 2015; Shumo *et al.*, 2019a). Second, earthworm farming can be profitable using only organic residual streams as feed, due to the high prices achieved by vermicompost (Sherman, 2018). Industrial scale insect farming in the Global North, on the other hand, at present frequently uses high-quality feeds to optimize economic efficiency and comply with EU regulation (Makkar *et al.*, 2014; Oonincx *et al.*, 2015; Dobermann *et al.*, 2017; Bosch *et al.*, 2020; Oonincx *et al.*, 2020), which calls for a food-versus-feed debate and may increase the overall environmental footprint of the food system (Gianotten *et al.*, 2020; Parodi *et al.*, 2022).

TABLE 2 Mineral content of earthworms and three species of commonly farmed edible insects

Data from:		Present review earthworms			Chia *et al.*, 2020 black soldier fly larvae	Sikora *et al.*, 2023 house cricket	Zielińska *et al.*, 2015 yellow mealworm
Mineral	n	mean	min	max	n = 12	n = 3	n = 3
Macro-minerals (% DM)							
Ca	74	0.662	0.044	5.030	2.039[b]	0.061[a]	0.041[a]
K	58	0.651	0.028	2.200	1.115[b]	0.810[c]	0.835[c]
Mg	42	0.229	0.014	0.820	0.362[b]	0.188[a]	0.304[c]
Na	40	0.721	0.002	5.770	0.109[a]	0.113[a]	
P	70	0.847	0.146	2.750	1.177[b]	0.523[a]	0.057[a]
Micro-minerals (mg/kg)							
Cu	38	432.9	1.5	12000.0	12.5[a]	16.3[a]	18.6[a]
Fe	37	3836.1	5.7	49100.0	284.2[a]	45.4[a]	32.9[a]
I	4	1252.3	0.4	2700.0	*0.7[a]	**0.7[a]	**0.4[a]
Mn	33	1596.7	1.3	30400.0	196.3[a]	9.62[a]	***11.0[a]
Se	3	4.0	0.4	9.0	*0.8[a]	0.53[a]	**0.7[a]
Zn	36	175.2	17.7	1200.0	180.1[c]	84.00[a]	112.0[a]

*Data from Finke, 2013 (n = 1); ** data from Finke, 2002 (n = 1); *** data from Latunde-Dada *et al.*, 2016 (n = 5); [a] mineral content is on average higher in earthworms; [b] mineral content is on average lower in earthworms; [c] mineral content is comparable to earthworms.

TABLE 3 Vitamin content of earthworms and three species of commonly farmed edible insects

Data from:		Present review earthworms			Finke, 2013 black soldier fly larvae	Finke, 2002 house cricket	yellow mealworm
Vitamin	n	mean	min	max	n = 1	n = 1	n = 1
Fat-soluble vitamins (IU/g)							
Vitamin A	4	4.01	0.33	7.33	*5.33[b]	**0.10[a]	**0.13[a]
Vitamin E	2	38.81	0.07	112.69	*2.99[a]	**63.58[b]	**61.94[b]
Water-soluble vitamins (mg/kg)							
Thiamine	2	14.50	14.00	15.00	19.85[b]	1.30[a]	6.30[a]
Riboflavin	2	152.00	147.00	157.00	41.75[a]	110.71[a]	21.26[a]
Niacin	2	507.00	358.00	656.00	182.99[a]	124.68[a]	106.82[a]
Pantothenic acid	2	17.00	16.00	18.00	99.23[b]	74.68[b]	68.77[b]
Pyridoxine	2	4.50	2.00	7.00	15.49[b]	7.47[b]	21.26[b]
Biotin	2	0.68	0.35	1.00	0.90[b]	0.55[c]	0.79[c]
Folic acid	2	1.25	0.50	2.00	6.96[b]	4.87[b]	4.12[b]
Cobalamin (B_{12})	2	4.00	4.00	4.00	0.14[a]	0.01[a]	0.17[a]

* Data from Shumo *et al.*, 2019b (n = 3), ** data from Pennino *et al.*, 1991 (n = 2 and 3, respectively); [a] vitamin content is on average higher in earthworms; [b] vitamin content is on average lower in earthworms; [c] vitamin content is comparable to earthworms.

The situation is different in the Global South, where fly species are being farmed fully on organic residue diets (Dzepe *et al.*, 2021). Third, to our knowledge no diseases have occurred in earthworm farming even though it is practiced at industrial scale for several decades. In contrast, disease outbreaks are becoming more problematic with the scaling up of insect production (Maciel-Vergara *et al.*, 2021).

One could argue that competition over residual streams by different upcycling pathways is likely to intensify as we move towards more circular food systems. In this line of reasoning, introducing earthworm farming would only add another competitor into this landscape. Our vision is that instead of highlighting competition between various upcycling pathways such as farming of earthworms, insects, fungi, bacteria or chemical processing, we should embrace the synergies that these technologies offer within an anthropogenic ecosystem of upcycling pathways. By combining the strengths of different organisms and processes according to the properties of a residual stream, we could achieve a higher value use in social, economic and environmental terms. To this end, earthworms could be combined with a number of other upcycling pathways. For example, a study found that rearing of black soldier fly larvae can be effectively coupled with subsequent vermiculture (Cappellozza *et al.*, 2019). The authors showed that feeding insect excreta to earthworms led to added value in terms of compost quality and earthworm protein. Earthworms have also been successfully employed to decompose spent mushroom substrates, a residual stream from the production of edible mushrooms (Hřebečková *et al.*, 2020; Purnawanto *et al.*, 2020). Thereby, spent mushroom substrate, which can cause nutrient leaching if left untreated, can be upcycled into earthworm protein and vermicompost (Ruangjanda *et al.*, 2022). A similar coupling of vermiculture can be imagined for organic residual streams from fermentation-farming of microalgae and bacteria, or digestate from bio-energy production.

10 The way forward

Embedding earthworms in the transition towards sustainable and circular food systems will require, among other things, overcoming bottlenecks in food safety, harvesting and processing, environmental sustainability, regulation, and consumer behaviour. As similar hurdles exist for farmed edible insects, and are currently being addressed in research agendas, we argue that earthworm farming could benefit from the knowledge and frameworks that are being generated for insects. For instance, food safety procedures developed in insect farming could be adapted to earthworm farming to reduce the risk of contamination with heavy metals, pesticides, pharmaceuticals and microbial pathogens (Finke *et al.*, 2015; van der Fels-Klerx *et al.*, 2018). This includes screening methods, pre-processing treatments for contaminated residual streams, and drying and processing equipment.

Other bottlenecks for up-scaling earthworm farming are linked to the processing steps described by Medina and Araque (1999), including harvesting, washing and voiding, killing and preservation. Harvesting presents a technical challenge because the trommel-sieves used for separating mature earthworms from vermicompost can become clogged if the vermicompost is too wet. Achieving optimal moisture is therefore crucial and may be difficult when heterogeneous residual streams are used. Harvested earthworms, as mentioned above, should be voided to increase protein content, particularly if mineral particles are present in the feed material. This process involves submerging harvested earthworms at around 20 °C for 24-48 hours in water with a low salt content, as high salt contents would kill the worms (Sherman, 2018). The water also needs to be aerated by a pump to maintain sufficient oxygen levels for earthworms to breathe through their skin. This process may be challenging and water-intensive with large volumes of earthworms. If no mineral particles are present in the feed, it may be possible and safe to process them without voiding of the gut. Next, the earthworms need to be killed and processed to meet food safety standards. Killing is often done by freezing, which is energy-intensive. Alternative options may be osmotic dehydration by salt or suffocation in CO_2. Ethical concerns should be considered in investigating these options. Finally, the dead earthworms need to be processed or preserved for food purposes, which has important implications for energy-use, nutritional quality and food safety. Oven-drying or freeze-drying are the most common practices for the preparation of earthworm meal. Freeze-drying of earthworms, as compared to oven drying, preserves unsaturated omega-3 fatty acids (Gunya *et al.*, 2016a), but the high energy-use involved affects the overall sustainability of earthworms as food (Tedesco *et al.*, 2019). Oven-, microwave-, or sun-drying (Suárez-Hernández *et al.*, 2016a), smoking (Paoletti *et al.*, 2003), ensiling (Ortega Cerrilla *et al.*, 1996b), or preservation of earthworms in salt may present less energy-intensive alternatives. Direct fresh processing of earthworms into sausages or burger patties, for instance, may be feasible with short producer-to-consumer distances for products which are sterilized by cooking before consumption. Depending on the feed material, earthworms may be contaminated with microbial pathogens and can transmit tapeworms and nematodes pathogenic to birds and mammals (Swati and Hait, 2018; Edwards and Arancon, 2022). Vermicomposting reduces microbial contamination by different mechanisms (Swati and Hait, 2018) and processing methods presenting a kill-step, such as oven-drying, microwave-drying, or cooking can further reduce contamination (Conti *et al.*, 2019; Tedesco *et al.*, 2020). Processing is also important for changes in consumer behaviour, as only an appealing product will convince the consumer. Information and awareness are key variables for earthworms to be accepted as an alternative protein source in human diets (Conti *et al.*, 2018; Russo *et al.*, 2020).

Finally, it is necessary to expand our knowledge on the environmental sustainability of earthworm farming. This includes identifying which combinations of earthworm species with residual streams are most productive, quantifying greenhouse gas emissions of these species-feed combinations, determining optimal substrate-to-earthworm ratios for protein production, and quantifying energy, water, N and P use (Tedesco *et al.*, 2019). The frameworks developed for farmed insects (Dortmans *et al.*, 2017; Mertenat *et al.*, 2019; Smetana *et al.*, 2021) can also be useful in this case.

11 Conclusion

We have demonstrated that earthworms are rich in protein with a complete profile of essential amino acids, and contain important fatty acids, minerals and vitamins. This composition indicates the substantial potential of earthworms as a future food from a nutritional standpoint. We argue that earthworms, given their capacity for upcycling organic residual streams to edible protein and valuable compost, should play a role in the transition towards circular food systems. Compared to edible insects, earthworms may provide several sustainability advantages in terms of energy-use, feed material, and the occurrence of diseases. Further research is necessary to optimize the productivity and nutritional composition of commonly farmed earthworm species feeding on different materials. In addition, greenhouse gas emissions and nutrient flows should be quantified to inform a sustainability assessment of earthworm farming as a protein source for human nutrition.

Supplementary material

Supplementary material is available online at:
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