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Production of feed protein from animal waste by earthworms

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The 84 Mt of cattle waste, 9 Mt of pig waste and 4–5 Mt of poultry waste produced annually in the U.K. create serious disposal problems. Research at Rothamsted since 1980 has shown that the earthworm *Eisenia foetida* and other species can break down these wastes rapidly under controlled conditions to provide valuable horticultural composts and high-grade protein suitable for animal feed.

The conversion of animal wastes into earthworm tissue is very efficient, a tonne of suitable animal wastes producing up to 100 kg of worms, equivalent on a dry-mass basis to a conversion efficiency of the order of 10 %. Earthworm dry matter is 60–70 % protein with a higher content of essential amino acids, such as lysine and methionine, than either meat or fish meal. The other constituents of worms are 6–11 % fat, 5–21 % carbohydrate, 2–3 % minerals and a range of vitamins, of which niacin and vitamin B_{12} are of particular value. Thus worms are a valuable potential source of animal feed if they can be produced economically.

Machinery for harvesting worms, methods of processing them into animal feed and successful feeding trials with fish and chickens are described.

1. Introduction

The large amounts of organic wastes produced by intensive animal production in the United Kingdom, which include 84 Mt of cattle waste, 9 Mt of pig waste and 4–5 Mt of poultry waste, cause major problems in disposal and a considerable potential for pollution of waterways. Charles Darwin (1881) was the first to emphasize the very important role that earthworms play in breaking down organic matter. The importance of earthworms in processing organic matter in compost heaps is well known but less familiar is the great abundance and value of earthworms in the breakdown process in trickling sewage filters (Terry 1951).

Work in recent years in the U.S.A. (Hartenstein *et al.* 1979; Neuhauser *et al.* 1979) has shown that earthworms can be used to break down activated sewage sludges to finely divided materials, and even more recently at Rothamsted that earthworms can be used to break down animal, vegetable and industrial organic wastes to useful composts (Edwards 1983).

The first to suggest that earthworms contained sufficient protein to be considered as animal food were Lawrence & Millar (1945), but it is only in the last ten years that fuller analyses of the body tissues of earthworms have been available to support this conclusion and the first successful animal feeding trial was by Sabine (1978).

2. Food value of worms

Since the initial work of McInroy (1971), there have been a number of analyses of the constituents of the tissues of different species of earthworms (Schulz & Graff 1977; Sabine 1978; Yoshida & Hoshii 1978; Mekada *et al.* 1979; Taboga 1980; Graff 1982). The overall composition of earthworm tissues does not differ greatly from that of many vertebrate tissues (table 1).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

The essential amino acid spectrum of earthworm tissues compares well with those from other currently used sources (table 2). Clearly the mean amounts of essential amino acids recorded are very adequate for a good animal feed as recommended by F.A.O.–W.H.O., particularly in terms of lysine and the combinations of methionine and cysteine, phenylalanine and tyrosine, all of which are important components of animal feeds. In addition, earthworm tissues contain a preponderance of long-chain fatty acids, many of which non-ruminant animals cannot synthesize, and an adequate mineral content (figure 1). They have an excellent range of vitamins and are rich in niacin which is a valuable component of animal feeds (table 3).

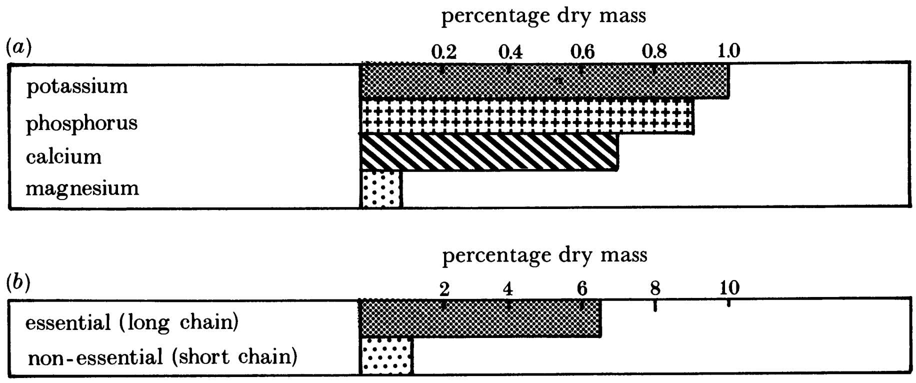

FIGURE 1. (*a*) Minerals in earthworms; (*b*) fatty acids in earthworms.

TABLE 1. COMPOSITION OF EARTHWORM TISSUE

water	78–88 %
protein	60–70 % (dry matter)
fat	6–11 % (dry matter)
carbohydrate	5–21 % (dry matter)
minerals	2–3 % (dry matter)
gross energy	16–24 kJ g^{-1} (dry matter)

TABLE 2. ESSENTIAL AMINO ACID CONTENT (GRAMS PER 100 g PROTEIN) OF EARTHWORM TISSUE

essential amino acid	W.H.O.–F.A.O. requirements of essential amino acids 1957–65	1973	McInroy (1971)	Schulze & Graff (1977)	Sabine (1978)	Yoshida & Hoshii (1978)	Mekada *et al.* (1979)	Taboga (1980)	Graff (1982)	Rothamsted	mean of all analyses
arginine	—	—	6.1	6.1	4.2	6.9	4.5	7.3	6.1	6.5	6.0
cysteine	2.0	[a]	1.8	1.4	2.3	0.8	—	1.8	1.4	0.7	1.5
histidine	—	—	2.2	2.3	1.6	4.3	1.6	3.8	2.3	3.0	2.6
isoleucine	4.2	4.0	4.6	4.7	2.6	4.7	4.3	5.3	4.7	4.1	4.3
leucine	4.8	7.0	8.1	8.2	4.8	8.7	5.0	6.2	8.2	8.3	7.2
lysine	4.2	6.5	6.6	7.5	4.3	8.7	5.9	7.3	7.5	6.5	6.8
methionine	2.2	[a]	1.5	1.8	2.2	1.6	1.9	2.0	1.8	2.8	2.0
phenylalanine	2.8	[b]	4.0	3.5	2.3	4.4	3.4	5.1	3.5	4.0	3.8
threonine	2.8	4.0	5.3	4.7	3.0	5.2	6.9	6.0	4.7	5.6	5.2
tryptophan	1.4	1.0	—	—	—	1.3	—	2.1	—	0.7	1.4
tyrosine	2.8	[b]	—	3.0	1.4	4.4	2.7	4.6	3.0	3.5	3.2
valine	4.2	5.0	5.1	5.2	3.0	5.1	5.1	4.4	5.2	4.7	4.7

[a] 3.5 Total for methionine + cysteine.
[b] 6.0 Total for phenylaniline + tyrosine.

Table 3. Vitamin composition (milligrams per kilogram) of earthworm tissues

niacin	358
riboflavin (B_2)	147
pantothenic acid (B complex)	16
thiamin (B_1)	15
pyridoxine (B_6)	2
vitamin B_{12}	4
folic acid	0.5
biotin (B complex)	0.35

3. Growth of worms in animal wastes

The life cycles of four species of worms that grow and reproduce well in organic wastes have been investigated thoroughly at Rothamsted. These are *Eisenia foetida* (Savigny), *Eudrilus eugeniae* (Kinberg), *Perionyx excavatus* (Gates) and *Dendrobaena veneta* (Rosa). The growth patterns of individual worms or whole populations followed sigmoid curves and the maximum protein production per unit time has been achieved by inoculating large volumes of animal wastes with relatively small numbers of young worms. Dry-matter conversion ratios of waste to worms as high as 10% for cattle and pig waste and 5% for poultry wastes have been achieved readily in the laboratory and would seem to be feasible ultimately on a field scale.

These earthworms can withstand many adverse environmental factors and on the basis of our research we have defined their environmental requirements within broad limits (table 4).

Table 4. Necessary conditions for good growth of *Eisenia foetida* in animal wastes

aerobicity
ammonia content less than 0.5 mg kg^{-1}
salt content less than 0.5%
temperature 15–20 °C
moisture content 80–90%
pH 5–9

4. Methods of production

The natural habitat of worms that break down organic matter is in heaps of decaying organic matter and compost heaps. These habitats follow a natural microbial decomposition process with a succession of micro-organisms and wide changes in temperature, with up to 70 °C being attained quite commonly. In such habitats, worm colonization is limited by temperature, populations are localized and biomass productivity is low. To produce earthworms, as a potentially commercial source of protein, such systems must be controlled environmentally and waste added periodically to enable earthworms to colonize all of the organic matter and utilize the micro-organisms in which they feed to the maximum.

Animal wastes range from almost liquid slurries through straw-based mixtures to relatively dry and finely dispersed mixtures such as those produced by laying chickens over deep litter systems. These wastes must be brought to a suitable moisture content and temperature and the ammonia and salt contents reduced to acceptable levels by leaching, composting or some other method, before the worms can be grown successfully.

Once these conditions are attained, worms may be grown by a variety of methods such as in ground-based beds of different sizes, in batch systems in boxes or crates or even in trickling filter systems similar to those used in sewage disposal. The choice of a system depends mainly on economic considerations, such as the cost of addition of wastes to breeding containers, worm harvesting and handling.

It is outside the scope of the present paper to deal with the technology of worm production in detail, but it has been found that the growth of worms in beds filled with animal waste to a depth of about 50 cm in successive shallow layers at regular intervals by automatically operated gantries is easy to manage. In colder climates some form of insulated housing is necessary. Different forms of batch production in crates or boxes are useful in some circumstances and systems of continuous processing of wastes with automatic addition and removal of wastes are being developed currently. The technology to maximize worm and compost production is an evolving one, but with the current engineering input holds considerable promise for development into highly productive non-laborious systems. The rapid rate of growth and multiplication of earthworms, and the efficient conversion of organic wastes into earthworm tissue protein, means that systems can be developed that use a minimum of labour or sophisticated technology. Moreover, earthworms seem to have few diseases, predators or parasites that might hinder maximum protein production.

The efficient productivity of earthworm protein depends mainly upon detailed knowledge of the population dynamics of the appropriate species, and upon the engineering of suitable production systems that involve small labour inputs. Considerable progress has been made towards the achievement of both these aims in research at Rothamsted and the National Institute for Agricultural Engineering, Silsoe.

5. Harvesting of earthworms from animal wastes

As the individual earthworms and earthworm populations grow, they fragment the animal wastes into finer and finer particles, producing eventually a peat-like material that has considerable potential in horticulture. A major problem is that worms grow best at relatively high moisture levels (80–90% moisture content) and it is not easy to separate worms mechanically from the finely divided organic matter at such high moisture contents.

Machinery for separating worms from fully worked organic materials has been developed at Rothamsted and the National Institute for Agricultural Engineering, Silsoe (Phillips 1985) and patented. The efficiency of this machinery in terms of percentage recovery of worms is very high. The machine that has been developed will at present separate worms from about one tonne of waste per hour and this machine is being automated and scaled up to increase this throughput. Until this automation has been achieved and until a rapid rate of separation of worms from waste is possible, the production of protein for animal feed from worms will remain an uneconomic process. Fortunately, it seems quite likely that this aim will be achieved within the coming year.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

6. Processing of worms for animal feed

The worms collected from the separating machinery may have small particles of waste on their bodies and are likely to contain waste in their guts. Hence, the first stage of all the methods of processing tested is to wash the worms thoroughly and leave them standing in water for a minimum of three hours, to completely evacuate the residual waste in their guts.

Various methods of processing the worms for animal feed have been developed and tested. Two of the methods tested produced a paste product and the four others a dry worm meal; all of these were acceptable for different uses and the ultimate choice of a method of processing must depend upon (i) the type of feed required, (ii) the cost of production of the protein, (iii) minimal loss of dry matter and (iv) minimal loss of nutrient value.

Pastes

(i) The first method tested was to blanch the worms in boiling water for one minute and incorporate 30% molasses together with 0.3% potassium sorbate to produce a paste. The molasses effect a lowering of the water activity to about A_W 0.90 and the addition of potassium sorbate reduces this further to approximately A_W 0.65. At this level, the growth of yeasts and moulds is inhibited, permitting indefinite storage of the product.

(ii) Another wet method tested was to incorporate 3% formic acid with the worms with thorough homogenization, then to allow it to ensile and eventually produce a very stable paste or liquid product.

Dry meals

(i) In this method a dry protein meal was produced by blanching worms in boiling water for one minute, then air-drying and grinding.

(ii) A dry meal was produced by freezing worms quickly, then freeze-drying and grinding them.

(iii) Another dry meal was produced by first killing worms by immersing them in acetone for one hour and then air- and oven-drying them at 95 °C before grinding.

(iv) A fourth type of dry meal was produced by killing worms, drying them in an oven at 95 °C and grinding.

All the methods tested gave a good product that could be used but there were variations in the dry-matter yield (grams of dry product per 100 g fresh worms). Killing worms in boiling water and then drying them in an oven resulted in the lowest dry matter of 11.6%. Freeze-drying produced a meal with 13.5% dry matter. Killing worms in acetone then drying them in air produced a dry matter of 14.5%, but after subsequent oven drying this fell to 12.8%. Killing and drying the worms in a hot-air oven gave the greatest dry-matter yield of 15.2%.

The effects of the different processing methods on the amounts of essential amino acids are summarized in table 5. Most of the methods had relatively little effect on the amounts of amino acids in the product although the lysine content was decreased slightly by ensiling with molasses, with the use of formic acid and by freeze-drying, compared with other methods. Clearly, a stable protein feed can be produced by any of the methods and the choice of method must depend on the use to which the protein is to be put.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

TABLE 5. AMOUNTS OF ESSENTIAL AMINO ACIDS (GRAMS PER 100 g PROTEIN) IN WORM TISSUES AFTER DIFFERENT PROCESSING METHODS

	processing method					
amino acid	molasses ensiling	formic acid ensiling	freeze-dried	acetone-dried	heat-dried	blanch and heat-dried
arginine	6.5	6.7	6.4	7.0	3.8	4.1
cysteine	0.3	0.5	0.5	0.3	0.5	0.4
histidine	2.8	2.7	2.7	2.5	2.3	2.3
isoleucine	4.2	4.3	4.0	4.3	4.4	4.3
leucine	7.3	7.1	6.9	7.5	8.3	8.5
lysine	5.4	5.9	5.7	6.1	6.2	6.5
methionine	1.6	1.1	1.2	1.2	1.1	0.9
phenylalanine	3.0	2.8	3.1	3.2	3.1	3.6
threonine	4.8	5.1	8.5	5.1	5.5	5.6
tyrosine	2.0	2.4	4.0	2.8	2.8	3.0
valine	5.1	4.9	4.7	5.0	5.5	4.6

7. ANIMAL FEEDING TRIALS

The main outlets suggested for utilization of earthworm protein have been in fish-farming and as protein supplements in poultry and pig feeds.

(*a*) *Fish-feeding trials*

The first trials involving the feeding of earthworms to fish were by Tacon *et al.* (1983), who used worms produced at Rothamsted to feed trout. The growth of trout fed only on *E. foetida*, *Allolobophora longa* (Ude) and *Lumbricus terrestris* L. was compared with that of fish fed on a commercial ration. Fish fed with frozen *A. longa* and *L. terrestris* grew as well or better than fish fed on commercial trout pellets. Trout did not grow well on a whole diet of freeze-dried *E. foetida*, although they grew much better on *E. foetida* that had been 'blanched' in boiling water before freezing (Stafford & Tacon 1985). Dried earthworm meal derived from *E. foetida* which had not been blanched could replace the fish meal component of formulated trout pellets at levels of inclusion between 5 and 30% without affecting growth of trout. The conclusion reached was that earthworms have potential both as a complete feed or protein supplement for trout or other fish. Hilton (1983) reported that trout did not grow well on another earthworm species, *Eudrilus eugeniae*, but there are some doubts about his experimental techniques, because other forms of protein supplement currently used commercially, such as blood meal, would have also been unsuccessful if used in the same way that he used worm protein. Guerrero (1983) reported that *Tilapia* fish grew better on diets containing earthworm protein supplements from *Perionyx excavatus* (Perrier) than those with fish meal supplements.

(*b*) *Chicken-feeding trials*

The first trials which assessed the growth of chickens on earthworm protein were reported by Harwood (1976) and Sabine (1978). They compared the use of worm meal with meat meal as a protein supplement for chickens and found no significant difference in growth on the two diets. Similar results were reported by Taboga (1980) and Mekada *et al.* (1979), who also reported that when worms were fed to older birds, egg production was maintained. Jin-you *et al.* (1982*a*) reported that chickens fed on earthworms put on weight faster than those given other diets (including fish meal), had more breast muscle and consumed less food.

These results have been confirmed by our collaborators at the Poultry Research Centre, Edinburgh and reported by Fisher (1985). In these experiments, chickens grew well, had a good mass gain per unit of food and an excellent nitrogen retention when fed on diets with levels of worm meal from 72–215 g kg^{-1} (figure 2).

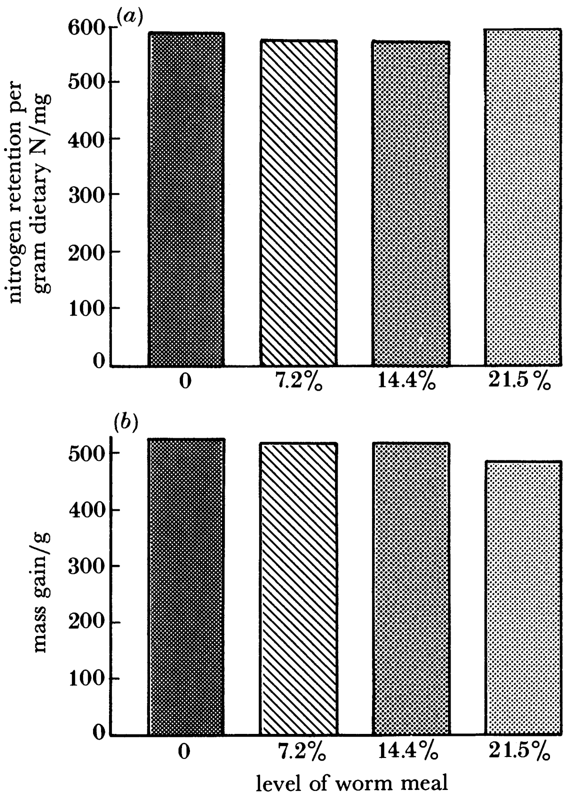

FIGURE 2. Growth of chickens on an earthworm protein diet. (*a*) Nitrogen retention; (*b*) mass gain.

(*c*) *Pig-feeding trials*

There have been only two trials reporting the growth of pigs on earthworm protein supplements. Harwood & Sabine (1978) and Sabine (1978) showed that in feeding trials with both starter and grower pigs, animals fed on an earthworm protein supplement grew equally well and had similar feed conversion ratios to those grown on commercial rations. Jin-you *et al.* (1982*b*) reported that piglets grew better on earthworm protein supplements than on others, and that older pigs had accelerated weaning, earlier oestrus in sows, increased disease resistance and a decreased incidence of white diarrhoea.

8. Economics of production of earthworm protein

There have been studies of the economics of production of earthworm protein (Fieldson 1985). The general conclusions were that earthworm production had the best prospects of good profits when done by larger farmers with considerable amounts of animal wastes. The most important criterion is that the worm meal must be produced at an economic price, although the value of the compost must be taken into account. Currently, the only labour-intensive part

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

of worm protein production is the harvesting process and this remains the main barrier to commercial production, but seems likely to be resolved in the near future.

In a computer analysis of the economic value of earthworm meal (table 6), based on its amino acid, fatty acid, mineral and vitamin content, it emerged that it is extremely valuable as feed for particular animals such as eels and young turkeys and has about the same value for fish, pig and poultry feed as fish meal or meat meal.

Table 6. Value of earthworm meal for different animal feeds

animal	maximum value/(£ t^{-1})
cows	130
ducks	183–218
broiler chickens	220–249
turkey (starter)	1011
turkey (finisher)	338
trout	404
eels	2000

Considerable thanks are due to J. M. Hill for amino acid analyses, M. E. Putnam, Roche Co. for vitamin analyses and A. Niederer, Meat Research Institute, New Zealand, for help with earthworm processing.

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