

Vermicomposting of fallow deer (*Dama dama* L.) manure using *Eisenia fetida* (Sav.) earthworms

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ABSTRACT

Given the need to ensure sustainable development in agriculture, waste should be managed properly. This also applies to manure from the breeding of non-conventional animal species. A study was conducted on the vermicomposting of fallow deer (*Dama dama*) manure using *Eisenia fetida* Sav. earthworms. The study assessed the effect of adding cellulose from cardboard and decomposed hay on the properties of the resulting vermicompost. In the study, clean fallow deer manure (FDM), fallow deer manure mixed with cardboard (FDMC) in a 1:1 ratio, and fallow deer manure mixed with decomposed hay (FDMH) in a 1:1 ratio were processed. The basic physico-chemical properties of the waste materials and vermicomposts were evaluated, as well as the population dynamics of compost earthworms depending on the substrate used in the vermireactor. The results indicate that *E. fetida* effectively processed the waste materials. Vermicomposting led to a decrease in pH and a reduction in salinity, indicating the progressive stabilization of organic matter. Compared to the initial material, the resulting vermicomposts were characterized by higher nitrogen, potassium, and magnesium content. The content of the analyzed trace elements in the vermicomposts was low, suggesting their potential use as fertilizer. The most favorable conditions for growth of the *E. fetida* population were observed in the treatment with cellulose (FDMC) added to the structural materials. The results indicate that fallow deer manure can serve as a useful substrate for vermicomposting, especially when combined with carbon-rich structural components.

Keywords: vermicomposting, fallow deer manure, *Eisenia fetida*, fertilizing properties.

INTRODUCTION

Modern agriculture and animal husbandry generate significant amounts of organic waste, the proper management of which is a key element of environmental protection, sustainable development, and the increasingly widespread adoption of the circular economy. Animal manure contains significant amounts of plant nutrients, including nitrogen, phosphorus, potassium, calcium, and magnesium, and can therefore serve as a valuable

source of fertilizer. Improper storage or direct application of this waste without prior stabilization can lead to odor emissions, nitrogen losses, leaching of biogenic compounds, and local soil and water pollution. For this reason, the safe processing of animal manure is a critical issue in waste management, soil protection, and modern agriculture (Enebe and Erasmus, 2023; Thirunavukkarasu et al., 2023).

The rational use of animal manure also aligns with the principles of the circular economy,

in which organic waste is treated as a potential source of raw materials rather than solely as an environmental problem. The nutrients contained in such materials can be reintroduced into the material cycle and utilized in crop production. This approach helps reduce the amount of waste requiring landfilling, alleviates environmental pressure, and significantly reduces the demand for mineral fertilizers, whose production is associated with high energy consumption and the use of natural resources. Biological methods of bio-waste treatment, including composting and vermicomposting, can therefore support the development of more sustainable agricultural systems (Bernal et al., 2009; Enebe and Erasmus, 2023). A similar approach was adopted in studies with vermicomposting presented as a technology for processing animal manure to enable the production of valuable organic material and to reduce the environmental pressure associated with its landfilling (Ergasheva et al., 2024a). The significance of this approach is also confirmed by research on the biotechnological processing of organic waste, which has shown that vermicomposting can result in organic fertilizer with lower salinity and a more beneficial effect on soil fertility than the source material (Ergasheva et al., 2024b).

Vermicomposting is a biological method for stabilizing and valorizing organic waste, carried out with the participation of concentrated populations of earthworms and microorganisms inhabiting the processed material. As a result of their activity, the organic matter undergoes decomposition, mineralization, and partial humification, and the final product is vermicompost – a stable organic material with potential fertilizing value. Compared to conventional composting, this process typically occurs at a lower temperature but requires conditions conducive to earthworm activity, particularly appropriate moisture levels and pH. One of the most commonly used species in such processes is *Eisenia fetida* (Sav.), which is characterized by a rapid reproduction rate and good adaptation to environments rich in organic matter (Domínguez and Gómez-Brandón, 2013; Usta and Güven, 2024).

The effectiveness of vermicomposting depends largely on the type and properties of the substrate processed. Animal manure varies in chemical composition, moisture content, fiber content, salinity, and the availability of plant nutrients, all of which can affect both earthworm growth and the quality of the final product.

Previous studies have focused mainly on manure from traditional livestock, such as cattle, sheep, goats, poultry, pigs, and horses. It has been shown that vermicomposting such materials can reduce organic carbon content and increase the relative concentration of selected macronutrients in the final product (Sharma and Garg, 2017; Garczyńska et al., 2020).

Currently, the potential for the biological processing of manure from wild, semi-wild, and farm- or agritourism-raised animals is much less well understood. This group includes fallow deer (*Dama dama* L.) manure, which may be produced locally at breeding farms, educational enclosures, and agritourism facilities. Fallow deer are a species of the deer family found in Poland in both wild populations and on farms. Data on the wild population indicate a marked increase in the species' numbers over recent decades: from approximately 2,300 individuals in the 1980s and about 5,400 in 1990 to approximately 36,000 individuals in 2024 (Grabowska, 2025). According to data from the Central Statistical Office (GUS) and hunting monitored by the Polish Hunting Association (PZŁ), the fallow deer population across all hunting districts totaled approximately 36,100 individuals in 2024, while in leased hunting districts, 24,800 individuals were recorded in 2024 and 24,000 in 2025. (GUS, 2024; Panek and Kolasiński, 2025).

Advisory materials indicate that the farm population of fallow deer in Poland may be approximately 12,000 head; however, this figure should be treated as an estimate due to the limited availability of current and regularly published statistical data for this type of breeding (Orlański, 2020). The importance of formal records for this type of animal is confirmed by the inclusion of cervids in the animal identification and registration system administered by the Agency for Restructuring and Modernization of Agriculture (2026).

Studies on the pasture-based management of fallow deer indicate that their impact on the soil environment may include changes in the content of organic carbon, nitrogen, phosphorus, potassium, calcium, and magnesium in the soil, as well as changes in soil enzymatic activity. However, this does not mean that their manure can be applied directly as fertilizer without first assessing its stability, salinity, fertilizing value, and chemical safety (Futa et al., 2024).

In the case of atypical animal manure, it is particularly important to determine whether it can

be vermicomposted as pure manure or whether it requires the addition of structural components. Carbon-rich materials, such as cardboard, hay, straw, or other plant waste, can improve the structure of the vermicomposting bed, increase aeration within it, and regulate the C:N ratio, thereby creating more favorable conditions for earthworm activity. These additives can also mitigate undesirable characteristics of the substrate itself, such as excessively high moisture content or oxygen-deprived conditions. The use of plant-based additives may therefore be significant not only structurally but also chemically, as carbon-rich components help balance nitrogen-rich substrates, reduce ammonia emissions, and improve the vermicomposting process (Kumari et al., 2025). A comparison of fallow deer manure alone with mixtures of fallow deer manure and cellulose and hay may therefore provide information on the suitability of these components in the biological valorization of this waste (Garczyńska et al., 2020; Azevedo et al., 2025;).

The assessment of vermicompost quality should include both the content of plant nutrients and parameters indicating the product's stability and environmental safety. The most important indicators include pH, salinity, carbon content, the C:N ratio, and the content of nitrogen, phosphorus, potassium, calcium, and magnesium, as well as the presence of potentially toxic trace elements. Excessive levels of metals such as Cd, Pb, Ni, Cr, or Cu may limit the agricultural use of organic fertilizers [Regulation of the Minister... 2024]. For this reason, trace element analysis is a crucial component of evaluating vermicomposts derived from less common animal-based substrates (Swati and Hait, 2017). Adding vermicompost to soil not only increases the availability of macro- and micronutrients but also improves soil structure and the stability of soil aggregates, thereby indirectly affecting physical properties, including soil water retention (Safadoust et al., 2025; Mulula et al., 2026).

Despite the growing number of studies on the vermicomposting of organic waste, there is still a lack of data on the processing of fallow deer manure, including using *Eisenia fetida*. This gap is significant because fallow deer manure can constitute a local stream of biowaste with potential fertilizing value, and its properties after vermicomposting have not been sufficiently described.

This study aimed to evaluate the feasibility of vermicomposting fallow deer manure using *E.*

fetida earthworms. The effect of adding cellulose from cardboard and hay on the properties of the resulting vermicompost was also determined. It was hypothesized that vermicomposting this manure could stabilize organic matter, reduce salinity and the C:N ratio, and improve the fertilizing value of the processed material.

MATERIALS AND METHODS

Study material

Mature *Eisenia fetida* (Sav.) compost earthworms, fallow deer (*Dama dama* L.) manure, and two organic additives – cardboard and hay – were used. The fallow deer manure served as the primary organic substrate, while the structure-forming additives were used to modify the properties of the mixtures subjected to vermicomposting.

Eisenia fetida (Sav.) earthworms

The experiment used mature specimens of the compost earthworm *Eisenia fetida*. These earthworms are an epigeic species, inhabiting the surface layers of organic matter, compost, manure, and decomposing plant debris. For this reason, it is one of the most commonly used species in vermicomposting processes, as well as in research on the processing of organic waste of agricultural and animal origin. *E. fetida* individuals have a segmented body, most often reddish-brown in color, and sexually mature individuals possess a distinctly developed clitellum, which in this experiment was used as the criterion for selecting mature individuals.

The suitability of *E. fetida* for vermicomposting stems from its high metabolic activity, rapid adaptation to environments rich in organic matter, and ability to convert diverse substrates into stable organic material. Literature emphasizes that vermicomposting depends not only on the activity of earthworms but also on associated microorganisms, particularly the gut microbiome, which participates in the decomposition of organic matter, the mineralization of components, and nitrogen cycling. Recent studies on the vermicomposting of cattle manure have shown that the activity of *E. fetida* and its gut microbiome promotes microbial succession, substrate stabilization, and the enrichment of the final product with minerals (Velásquez-Chávez et al., 2025).

In studies conducted in reactor systems, *E. fetida* is identified as one of the key species used for vermicompost production due to its high adaptability, high reproductive rate, and minimal space requirements. Optimal conditions for this species typically include a moist, well-aerated environment with a pH close to neutral or slightly alkaline. These parameters are important because excessive dryness, extreme pH levels, excessively high salinity, or an unfavorable substrate structure can limit earthworm activity and the rate of organic matter decomposition (Usta and Güven, 2024).

The experiment used earthworms from the parent stock of the Department of Agricultural Fundamentals and Waste Management at the University of Rzeszów. The selection of mature individuals was intended to minimize variability resulting from different developmental stages of the earthworms and to ensure an active population capable of intensively processing organic material. Details of the earthworms used are provided in the *experimental design* section.

Characteristics of fallow deer manure

The primary substrate used in the experiment was shredded fallow deer (*Dama dama*) manure, referred to hereafter as FDM (*fallow deer manure*). This material originated from a fallow deer farm located in the village of Korczyna (49.7168° N, 21.8107° E), operated by a private farm.

FDM was treated as an unconventional organic waste of animal origin. Compared to cattle, horse, sheep, or goat manure, it is much less documented in the scientific literature, particularly in the context of its biological processing and subsequent use as fertilizer.

From a fertilization perspective, FDM can be considered a material rich in organic matter and minerals; however, their composition depends on the animals' diet, the season, the husbandry system, and storage conditions. Studies on the farm management of fallow deer indicate that FDM influence nutrient cycling, including the content of organic carbon, nitrogen, phosphorus, potassium, calcium, and magnesium in the soil. Pasture studies have also shown that deer droppings and urine can affect soil pH and enzymatic activity, confirming the importance of this type of material in the local cycle of organic matter and nutrients (Futa et al., 2024).

Another important characteristic of herbivore droppings is that their composition depends on

the quality of the feed consumed. In the case of fallow deer, correlations have been demonstrated between the nitrogen content in droppings and the quality of the diet and the animals' housing conditions, which means that droppings may exhibit chemical variability (Sacconi et al., 2007).

Description of the experiment

Vermicomposting of fallow deer droppings

The experiment was conducted using three substrate combinations, in three replicates (Table 1).

- FDM – fallow deer manure + *E. fetida* earthworms,
- FDMC – fallow deer manure mixed with shredded cardboard (1:1) + *E. fetida* earthworms,
- FDMH – fallow deer manure mixed with waste hay (1:1) + *E. fetida* earthworms.

Cardboard and hay served as additives intended to modify the substrate structure, increase the proportion of plant matter, and create more favorable conditions for earthworm activity (Kostecka, 2000; Garczyńska et al., 2020). This experimental design allowed for a comparison of FDM with mixtures containing carbon-rich components.

Before setting up the experiment, FDM, cellulose, and hay were shredded and moistened to obtain a more homogeneous material and ensure conditions suitable for earthworm activity. The experiment was conducted in plastic containers serving as vermicomposters (24.5 × 18 × 12.5 cm). A large-mesh nylon net was placed in each container, allowing earthworms free access to the food material while facilitating the separation of the processed substrate from the rest of the substrate. Before introducing the earthworms, individuals were weighed separately, allowing equalization of the initial total biomass across the different treatment groups. After placing the earthworms, the upper part of the containers; including the nylon nets containing the substrates; was covered with a stratification layer. The containers were then sealed with perforated lids, which ensured air exchange and minimized the risk of earthworms escaping. Throughout the experiment, substrate moisture was monitored, as it is one of the key factors influencing the activity of *E. fetida* and the vermicomposting process. When necessary, the substrates were moistened (sprayed) with water to maintain conditions conducive to feeding, movement, and the processing of organic matter by the

Table 1. Experimental design

Treatment	Substrate composition with a stratification layer*	Number of vermicomposter replicates	Initial no. of <i>E. fetida</i> per vermicomposter	Initial <i>E. fetida</i> biomass per vermicomposter
FDM	400 g of fallow deer droppings			9.35 ± 0.12 g
FDMC	200 g of fallow deer droppings + 200 g of cardboard	3	20	9.88 ± 0.21 g
FDMH	200 g fallow deer droppings + 200 g hay			9.53 ± 0.27 g

Note: *2 kg each of “Kronen” universal gardening soil (lightweight with slow-release fertilizer, completely water-soluble), enriched with micronutrients (iron, boron, manganese, molybdenum, copper, zinc) and a moisture retainer that facilitates absorption and even distribution of water in the substrate, pH 5.0–6.0, produced from high-moor peat.

earthworms. The vermicomposters were kept in an air-conditioned chamber (temperature 20±0.5 °C, humidity 70%). The experiment was conducted from september to december 2024.

The experiment lasted for 4 months, and the population dynamics of *E. fetida* in the individual treatments was assessed once per month. For this purpose, the contents of each vermireactor were manually sorted to separate mature individuals, immature individuals, and cocoons. All earthworms and cocoons found were counted and then weighed. Data on the abundance and biomass of mature individuals, immature individuals, and cocoons were analyzed separately for each observation date and substrate treatment. Assessing earthworm abundance and biomass is important because the population size and activity of *E. fetida* influence not only the rate of substrate processing but also microbial structure and the course of mineralization and humification during vermicomposting (Devi et al., 2023).

Physicochemical analysis of manure and the resulting vermicomposts

Selected physicochemical properties were determined in the initial material and in the resulting vermicomposts. The scope of the analyses included pH, salinity, and the content of carbon, nitrogen, phosphorus, potassium, calcium, magnesium, and selected micronutrients and trace metals. These determinations were performed to assess the changes occurring during the vermicomposting process and to determine the potential fertilizing value and environmental safety of the resulting products.

The pH of the substrates was determined potentiometrically in water, while salinity was determined using a conductometric method and

expressed as NaCl content. Carbon content was determined using a Vario EL-CUBE elemental analyzer. Total nitrogen was determined using the Kjeldahl method, while nitrate nitrogen (N-NO₃) was determined colorimetrically in an aqueous extract. The C:N ratio was calculated based on the determined carbon and nitrogen contents. Phosphorus content was determined colorimetrically using the vanadium-molybdenum method. Potassium, calcium, and magnesium were determined by atomic absorption spectrometry following prior mineralization of the samples in a mixture of concentrated mineral acids (HNO₃:HClO₄:H₂SO₄) in a volume ratio of 20:5:1. The Cu, Cr, Ni, Cd, and Pb contents were determined using atomic absorption spectrometry, with the determination of Cd, Pb, Cr, and Ni preceded by the concentration of the analytes in the organic phase of methyl isobutyl ketone (MIBK). All determinations were performed in accordance with the analytical procedures used for agricultural and organic materials (MAFF, 1981).

Statistical analysis

The results of the statistical analyses are presented as mean values from three replicates with standard deviation (mean ± SD). Calculations were performed using Statistica 13.1. The significance of differences between the experimental treatments was assessed using one-way analysis of variance (ANOVA). When significant differences were found, Tukey’s post hoc test was used to compare the mean values between groups. The analysis was conducted for the monitored physicochemical parameters and the trace metal content in the initial material and the resulting vermicomposts. Differences were considered statistically significant at $p \leq 0.05$.

RESULTS AND DISCUSSION

Changes in the physicochemical properties of the tested substrates

The vermicomposting process affected most of the analyzed physicochemical properties of the tested substrates. Changes in selected substrate parameters before and after the vermicomposting process are presented in Table 2. For all experimental treatments, a decrease in pH and salinity was observed, as well as a decrease in organic carbon content and a reduction in the C:N ratio. At the same time, following the completion of the vermicomposting process, an increase in the content of phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) was observed, although the extent of these changes depended on the initial composition of the substrate.

The pH of all analyzed initial materials was close to neutral and ranged from 7.5 to 7.6. After the vermicomposting process was completed, a decrease in pH was observed to 6.3 in the FDM variant, 6.4 in the FDMC variant, and 6.8 in the FDMH variant. The decrease in pH may be associated with the formation of organic acids during the decomposition of organic matter, as well as with intense biochemical transformations occurring under the influence of microorganisms and earthworms. In this process, complex organic compounds are degraded, and intermediate products are released, which may contribute to environmental acidification. Similar trends have been observed in numerous studies on the vermicomposting of animal manure, where the activity of *E. fetida* and co-occurring microflora led to significant changes in the pH of the material and intensive transformation of organic matter (Domínguez and Gómez-Brandón, 2013; Sharma and Garg, 2017; Garczyńska et al., 2020). The results obtained indicate that the vermicomposting process affects not only the nutrient content but also the chemical properties of the final product, which are important for its fertilizing value and suitability for crop production.

One of the most significant changes observed during vermicomposting was a marked reduction in the salinity of the tested substrates. In the FDM treatment, this parameter decreased from 4.6 to 0.9 g NaCl·dm⁻³; in the FDMC treatment, from 5.1 to 1.4 g NaCl·dm⁻³; and in the FDMH treatment, from 4.9 to 1.5 g NaCl·dm⁻³ ($p \leq 0.05$). This corresponds to reductions of approximately 80%,

73%, and 69%, respectively. Such a significant reduction in salinity indicates the beneficial effect of vermicomposting on the chemical properties of the processed material. Excessive salt concentration can negatively affect seed germination, root system development, and the uptake of water and nutrients by plants (Rehman et al., 2023).

The carbon content decreased in all treatments. In FDM, it decreased from 36.340 mg·dm⁻³ to 34.600 mg·dm⁻³; in FDMC, from 49.181 mg·dm⁻³ to 40.866 mg·dm⁻³; and in FDMH from 53.460 mg·dm⁻³ to 44.128 mg·dm⁻³, corresponding to a decrease of approximately 17–24% ($p \leq 0.05$).

A decrease in carbon content is a typical effect of the biological decomposition of organic matter during vermicomposting. It results primarily from the intense activity of microorganisms and earthworms, as a result of which some of the organic carbon undergoes mineralization and is released into the atmosphere as CO₂ through respiration. At the same time, the more labile fractions of organic matter are transformed, leading to a decrease in the total carbon content of the substrate and a simultaneous increase in the proportion of more stable humic compounds (Patel et al., 2024).

Significant changes in nitrogen (N) content were also observed during the vermicomposting process. In the FDM treatment, the increase was moderate - from 1.580 to 1.730 mg·dm⁻³ - while the treatments with organic additives showed a significantly greater increase in nitrogen content. In the FDMC treatment, the N content increased from 1.870 to 2.085 mg·dm⁻³, and in the FDMH treatment from 1.980 to 2.240 mg·dm⁻³ ($p \leq 0.05$). The increase in nitrogen content in the variants with cellulose and hay additives may indicate intensified mineralization and nitrification processes in a more diverse organic substrate. These additives improve the structure and oxygen conditions, which promotes the activity of microorganisms responsible for the transformation of nitrogen compounds. As a result, the proportion of readily available mineral forms of this element in the final product increases. Vermicomposting promotes nitrogen transformation through the synergistic interaction of earthworms and microorganisms, which may increase the availability of mineral forms in vermicompost (Domínguez and Gómez-Brandón, 2013). Additionally, Edwards et al. (2011) emphasize that the activity of *E. fetida* accelerates the decomposition of nitrogen-containing organic compounds and promotes their conversion into forms that are available to plants,

which translates into an increase in the fertilizing value of the final product.

The quality of the vermicomposts obtained was also associated with an increase in the content of phosphorus, potassium, calcium, and magnesium. The most pronounced increase in phosphorus was observed in the FDMH treatment, where its content rose from 648 to 799 $\text{mg} \cdot \text{dm}^{-3}$ ($p < 0.05$). Potassium also showed a significant upward trend in all variants: from 843 to 1.311 $\text{mg} \cdot \text{dm}^{-3}$ in FDM, from 944 to 1.470 $\text{mg} \cdot \text{dm}^{-3}$ in FDMC ($p > 0.05$), and from 979 to 1.509 $\text{mg} \cdot \text{dm}^{-3}$ in FDMH ($p < 0.05$). For magnesium, the highest increase was also observed in the FDMH variant – from 221 to 478 $\text{mg} \cdot \text{dm}^{-3}$ – which indicates particularly intense transformations in this system.

The observed increase in the relative content of mineral nutrients can be explained by the simultaneous action of two processes: the mineralization of organic matter and the reduction in the total mass of the substrate during vermicomposting. As the organic fractions decompose, biogenic elements are released and converted into more available forms, resulting in their concentration in the final product.

A similar mechanism for enriching vermicompost with macronutrients was described in studies by Garczyńska et al. (2020) and Usta and Güven (2024), who indicated that earthworm activity and the intensive degradation of organic matter led to the concentration of nutrients in the final product. The authors emphasize that vermicomposting not only stabilizes organic matter but also increases its fertilizing potential by improving the availability and concentration of key elements. Kokkora et al. (2008) point out that the use of compost derived from municipal and agricultural waste in agriculture may allow for a partial substitution of N and K. However, after repeated application of compost in high doses, potential problems with soil salinization may arise. In the studies conducted, the vermicomposting process revealed no such risk.

A comparison of the treatment groups indicated that the addition of hay and cellulose favorably modified the course of changes in the substrate. Pure FDM also transformed; however, the most favorable changes in terms of increases in N, P, and Mg, as well as a reduction in the C:N ratio, were observed in the FDMC and FDMH treatments. Bellitürk et al. (2026), when comparing the performance of various substrates subjected to vermicomposting, noted that paper waste proved

to be the least beneficial material. The present study also highlighted the greater benefit of hay compared to cardboard. It is worth noting that the latter contains only a small amount of nitrogen. Nevertheless, the use of paper waste generally does not adversely affect the yield of cultivated plants, as confirmed by Quaye et al. (2011) in their studies on shrub willow.

Shredded cardboard in the FDMC substrate increases the material's porosity, improves oxygen access, and reduces the compaction of the compost mass. Earthworms prefer well-aerated substrates with a loose structure, as this facilitates their movement and the activity of microorganisms responsible for the decomposition of organic matter.

The increase in nutrient content in vermicompost is consistent with the findings of Marlina et al. (2024), who demonstrated that the vermicomposting process involving *E. fetida* contributes to an increase in macronutrient content and an improvement in the microbiological quality of products derived from dairy sector waste. The observed increase in nutrient content can be explained by the intensive mineralization of organic matter and the biological activity of earthworms, which, through digestive processes and interaction with microorganisms, accelerate the decomposition of complex organic compounds. As a result, nutrients are converted into forms more readily available to plants, thereby increasing their bioavailability. The results confirm that vermicomposting is an effective method for valorizing organic waste, leading to the production of a material with enhanced agronomic value and greater suitability for crop production.

Similar relationships were described by Vavouraki and Kornaros (2023), who, in analyzing mixtures of digested slurry and cattle manure, demonstrated that the presence of *E. fetida* promotes an increase in the nitrogen, phosphorus, and potassium content of the final material. The authors emphasized, however, that both the direction and magnitude of these changes depend largely on the type of substrates used and their relative proportions, indicating the significant role of input composition in shaping the properties of the resulting vermicompost.

The C:N ratios obtained at the end of the experiment, which were close to 20, can be interpreted as a sign of the progressive stabilization of organic matter and the maturation of the vermicompost. Telila and Shifera (2025) point out that a decrease in the C:N ratio, a decline in organic

Table 2. Changes in the physicochemical properties of growing media before and after vermicomposting

Selected characteristics		Substrate under study	FDM	FDMC	FDMH	
pH		Initial material	7.5±0.5 ^a	7.6±0.6 ^a	7.5±0.4 ^a	
		Vermicompost	6.3±0.6 ^a	6.4±0.9 ^a	6.8±0.6 ^a	
Salinity NaCl [g· dm ⁻³]		Initial material	4.6±0.3 ^a	5.1±0.5 ^a	4.9±0.7 ^a	
		Vermicompost	0.9±0.3 ^b	1.4±0.4 ^b	1.5±0.4 ^b	
C	mg·dm ⁻³	Initial material	36.340 ± 245 ^a	49.181 ± 243 ^a	53.460±116 ^a	
		Vermicompost	34.600 ± 236 ^a	40.866 ± 144 ^b	44.128 ± 213 ^b	
N		Initial material	1580±126 ^a	1870±212 ^a	1980±194 ^a	
		Vermicompost	1730±142 ^a	2085±235 ^b	2240±198 ^b	
P		Initial material	547±33 ^a	635±61 ^a	648±56 ^a	
		Vermicompost	607±63 ^a	706±42 ^a	799±78 ^b	
K		Initial material	843±33 ^a	944±32 ^a	979±34 ^a	
		Vermicompost	1311±45 ^b	1470±58 ^b	1509±67 ^b	
Ca		Initial material	680±43 ^a	740±43 ^a	787±56 ^a	
		Vermicompost	732±21 ^a	820±91 ^a	811±44 ^a	
Mg		Initial material	144±14 ^a	232±17 ^a	221±19 ^a	
		Vermicompost	268±8 ^a	450±25 ^b	478±36 ^b	
C:N		Initial material	23±1 ^a	26.3±1 ^a	27±4 ^a	
		Vermicompost	20±1 ^b	19.6±0.7 ^b	19.7±1.6 ^b	

Note: aa, bb – no statistically significant differences, ab – statistically significant differences.

carbon content, and a simultaneous increase in nitrogen, phosphorus, and potassium content are characteristic indicators of the effective biotransformation of organic waste carried out with the participation of *E. fetida*.

Similar relationships have also been observed in other studies on the vermicomposting of ruminant manure and various types of organic waste (Kostecka 2000; Sharma and Garg, 2017; Garczyńska et al., 2018, 2020), where a decrease in the C:N ratio was consistently demonstrated as a result of intensive mineralization and stabilization of organic matter.

A similar trend was described by Velásquez-Chávez et al. (2025), who observed a marked decrease in organic matter and organic carbon content, an increase in total nitrogen content, and a reduction in the C:N ratio from 27.13 to 12.40 during the vermicomposting of cattle manure. These results confirm that a reduction in the C:N ratio is one of the key indicators of maturity and quality of the final product in vermicomposting processes.

Bendouma et al. (2021) observed a marked decrease in the C:N ratio in degraded soils amended with paper industry waste, but at the same time noted a significant increase in organic carbon content.

The importance of the initial C:N ratio for the quality of the final product is confirmed by the studies of Dume et al. (2023), who analyzed the composting and vermicomposting of materials

with different C:N ratios. The results showed that the initial composition of the substrates affects not only the properties of the resulting vermicompost but also the rate of organic matter decomposition and the conditions for earthworm development.

Trace element content in vermicomposts

In addition to selected physicochemical parameters, the content of selected trace elements in the final vermicomposts was also assessed, as their presence may determine the environmental safety and potential agricultural suitability of the resulting products. The results of the analyses for Cu, Cr, Ni, Cd, and Pb are presented in Table 3.

The content of trace elements in the final vermicomposts derived from FDM was low and did not differ significantly among the treatments. Cu values ranged from 13.4 to 16.1 mg·kg⁻¹ dry weight, Cr from 5.3 to 5.9 mg·kg⁻¹ dry weight, and Pb from 12.9 to 13.8 mg·kg⁻¹ dry weight. The Ni and Cd contents remained below the method's limit of quantification. These results indicate that the substrates used did not cause excessive accumulation of the analyzed trace elements in the final products.

Assessing trace metal content is important because even material with a favorable fertilizer composition may have limited agricultural applications if it contains excessive amounts of potentially toxic elements. Pursuant to the Regulation

of the Minister of Agriculture and Rural Development dated August 9, 2024, on the implementation of certain provisions of the Act on Fertilizers and Fertilization, the permissible content of contaminants in organic and organic-mineral fertilizers, organic and organic-mineral plant growth aids, and post-fermentation products must not exceed: 100 mg Cr, 5 mg Cd, 60 mg Ni, 140 mg Pb, and 2 mg Hg per kg of dry matter of the product (Table 3).

Data from the literature confirm the importance of monitoring trace metals in vermicompost. Swati and Hait (2017) point out that during the vermicomposting of various organic wastes, not only does the total metal content change, but their chemical forms and bioavailability also undergo transformations, which may determine the actual environmental risk associated with the use of the final product. Similar observations were presented by Wang *et al.* (2017), who demonstrated that vermicomposting of cattle manure with *E. fetida* can reduce the total content of Cd, Pb, and Cr and limit the proportion of more mobile fractions of Cd and Pb. In this context, the low levels of Cu, Cr, and Pb, as well as Ni and Cd values below the limit of quantification in the vermicomposts studied, indicate that the processing of fallow deer manure with *E. fetida* did not lead to a deterioration in the chemical safety of the final product.

The addition of cellulose or hay did not increase the trace element content in the final vermicompost. A similar approach was used by Srivastava *et al.* (2024), who, in their evaluation of vermicompost derived from mixtures of agricultural waste and digestate, considered both the increase in nutrient content and the risk analysis associated with the presence of trace elements. The authors demonstrated that enriching the product with N, P, K, Mg, and Ca can go hand in hand with a low

environmental risk from metals, provided their concentrations remain below permissible limits.

The absence of significant differences in the analyzed trace elements among the vermicompost treatments suggests that the addition of cellulose and hay did not increase the risk of metal accumulation. This is important from the perspective of the practical use of such products, as structural additives should improve process conditions but should not compromise the chemical safety of the final product. A similar approach to evaluating vermicomposts made from animal manure was used in studies on vermicomposts from Cameroonian sheep manure, where, in addition to fertilizing properties, the content of trace metals was also analyzed as a criterion for product quality and safety (Kostecka, 2000; Garczyńska *et al.*, 2020).

Population dynamics of *Eisenia fetida* (Sav.)

The population dynamics of *E. fetida* differed significantly depending on the substrate composition in the vermicomposters (Figure 1). The initial population size was comparable across all treatments; however, at subsequent observation time points, the most pronounced increase was observed in the FDMC substrate with added cellulose (in cardboard). In this variant, the final earthworm population size increased by over 1.520% compared to the initial value. In the FDMH substrate with added hay, intense population growth was also observed—initially amounting to approximately 690% but decreasing to about 505% in the final phase of the experiment. The lowest growth was observed in the (FDM) treatment, containing only fallow deer manure, where the population increase reached approximately 220% relative to the initial value. The results clearly indicate that the addition of

Table 3. Trace element content in the resulting vermicomposts [mg kg⁻¹ dry matter]

Trace elements	Requirements according to the Regulation.* Permissible content [mg kg ⁻¹ dry matter] in mg per kg of dry matter of organic fertilizer	Characteristics of vermicomposts		
		FDM	FDMC	FDMH
Cu	-	13.4±2.2 ^a	14.8±2.9 ^a	16.1±1.7 ^a
Cr	100	5.3±0.4 ^a	5.8 ± 1.1 ^a	5.9 ± 1.4 ^a
Ni	60	<2.9 ^{**}	<3 ^{**}	<3 ^{**}
Cd	5	<0.40 ^{**}	<0.40 ^{**}	<0.40 ^{**}
Pb	140	12.9±2.8 ^a	13.5±1.8 ^a	13.8±2.2 ^a

Note: aa, bb – no statistically significant differences; ab – statistically significant differences; * Regulation of the Minister of Agriculture and Rural Development of August 9, 2024; ** results obtained below the method's limit of quantification.

cellulose-based materials significantly promoted the growth of the *E. fetida* population by creating more stable and favorable environmental conditions. Similarly, Kostecka (2000), in studies conducted in ecological boxes, highlighted the significant impact of cellulose on population growth, biomass, and reproductive parameters.

At the same time, it was observed that vermicomposting FDM with the addition of cellulose and hay significantly increased the reproduction of compost earthworms, as confirmed by the significantly higher number of cocoons in the FDMC and FDMH treatments ($p < 0.05$) (Figure 2). This effect can be attributed to an improvement in the physical structure of the substrate, better aeration, and stabilization of moisture conditions, as well as increased availability of readily digestible organic matter. Such conditions favor both the metabolic activity of adult worms and the survival of juvenile forms developing from cocoons.

The results obtained indicate that the addition of cellulose created more favorable conditions

for the growth of the *E. fetida* population, a finding supported by the literature (Kostecka 2000, Garczyńska et al. 2018). Garczyńska et al. (2020), on the other hand, confirmed the positive effect of hay on the abundance of *D. veneta* in a substrate containing Cameroonian sheep manure.

Rahman and Hajam (2024) also emphasize the importance of substrate composition for the development of *E. fetida*, demonstrating that different proportions of kitchen waste, manure, and rice straw significantly affect survival, growth, and the production of cocoons and juveniles. It indicates that both the type and proportions of organic additives determine not only the quality of the resulting vermicompost but also the population dynamics of earthworms.

The results obtained in this study suggest that cellulose-based additives create particularly favorable conditions for the development of *E. fetida*, likely by improving the substrate structure, increasing the proportion of the stable organic fraction, and providing a suitable

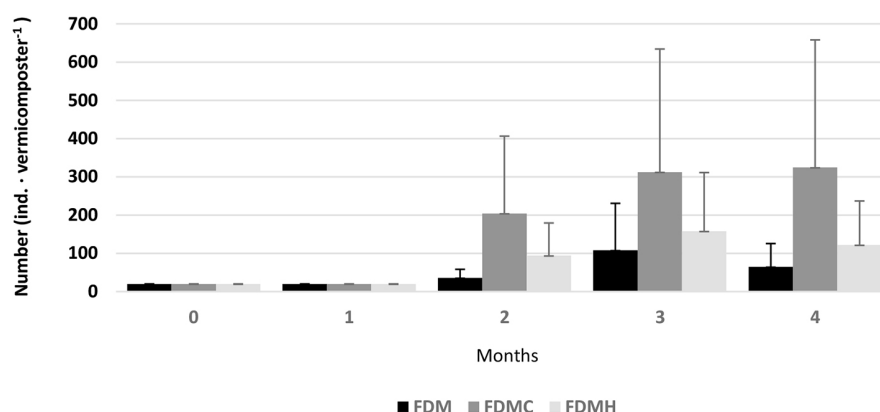


Figure 1. Population dynamics of *E. fetida* in different treatments (fallow deer manure (FDM), fallow deer manure with cardboard (FDMC) and fallow deer manure with hay (FDMH)) during vermicomposting over 4 months

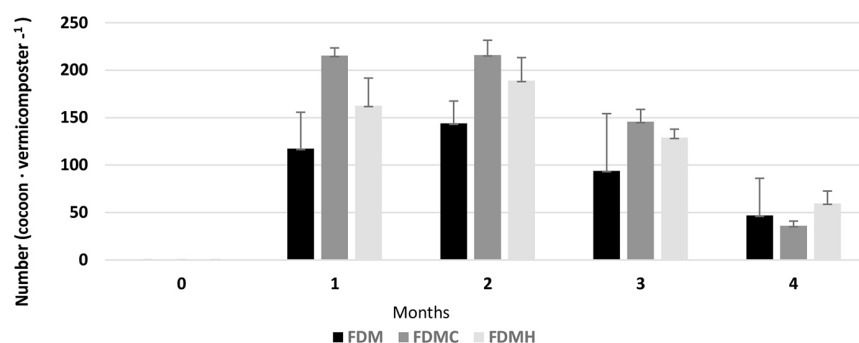


Figure 2. Dynamics of *E. fetida* cocoon numbers in different treatments (fallow deer manure (FDM), fallow deer manure with cardboard (FDMC) and fallow deer manure with hay (FDMH)) during vermicomposting over 4 months

environment for the development of juveniles. Bedell et al. (2023) emphasize that the initial organic matter content can significantly modify earthworm activity and influence the reproduction of *E. fetida*, which is consistent with the observations obtained in this experiment.

The addition of hay was beneficial for population growth, although its effect was weaker than that of cellulose. These differences may result from varying rates of decomposition and nutrient availability. The observed biological changes were consistent with trends in the chemical transformations of the substrates – the organic additives used intensified decomposition, which increased nutrient availability and thus supported earthworm population growth.

CONCLUSIONS

The results confirm that vermicomposting can be a useful method for the biological treatment of such atypical animal waste as fallow deer manure, as following:

1. The vermicomposting process significantly affected the physicochemical properties of the three substrates analyzed, leading to their marked stabilization and nutrient enrichment.
2. In all experimental treatments, a decrease in pH and salinity was observed, indicating an improvement in the quality of the final product and its greater suitability for agricultural applications.
3. During the vermicomposting process, the organic carbon content and the C:N ratio decreased, indicating intensive mineralization of organic matter and its transformation into more stable humic forms.
4. An increase in the content of macronutrients (N, P, K, Ca, Mg) was observed, resulting from the concentration of mineral components due to the reduction in organic matter and their release as a result of earthworm and microorganism biological activity.
5. The most favorable changes in the quality of the final product and the dynamics of chemical transformations were observed in the treatments with the addition of structure-forming materials (FDMC and FDMH), which highlights the importance of a suitably diversified substrate.
6. The addition of cellulose-based materials (cardboard and hay) significantly improved the

substrate structure, increasing its aeration and moisture stability, which promoted the intensification of biological processes.

7. The treatment with cellulose addition showed the highest increase in the population size of *Eisenia fetida*, confirming particularly favorable living conditions for this species in this system and the high suitability of such materials for vermicomposting.
8. The substrates used did not cause excessive accumulation of heavy metals, and their content in the final vermicompost remained at an environmentally safe level, confirming their suitability for agricultural use.

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