Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2026, 20(9), 476–489
https://doi.org/10.12913/22998624/224466
ISSN 2299-8624, License CC-BY 4.0

Received: 2026.05.18
Accepted: 2026.07.10
Published: 2026.08.01

Elements of post-fermentation slurry vermicomposting technology and its impact on fertilizer value

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ABSTRACT

The intensification of biogas production leads to increased production of digestate – a by product of anaerobic digestion – whose management poses a significant environmental and economic challenge. In the context of the transition toward a circular economy, there is a growing need to develop technologies that enable the transformation of this material into a product with greater utility. One promising solution is vermicomposting, which enables biological stabilization of digestate and improves its fertilizing properties. In the conducted studies, *Dendrobaena veneta* earthworms were used in various substrate compositions containing digestate, enabling both an assessment of the process's effectiveness and an evaluation of changes in the digestate's physicochemical properties and the dynamics of the earthworm population's development. The resulting vermicompost was subjected to agronomic analysis by evaluating its effect on the germination and growth of common corn (*Zea mays* L.) seedlings as an indicator plant. The results indicate that appropriately selected proportions of substrates with digestate intensify organic matter transformation within them and increase the fertilizing value of the final product. From an economic perspective, this technology can help reduce digestate management costs, increase its market value, and improve the environmental efficiency of biogas plant operations, aligning with the principles of the circular economy.

Keywords: agricultural biogas plants, digestate, waste management, vermicomposting technology, *Dendrobaena veneta*, economic efficiency, waste value-added, sustainable agriculture.

INTRODUCTION

Environmental protection and the growing energy demand necessitate the introduction of renewable energy sources (RES). Although Poland's energy system still relies heavily on fossil fuels, particularly coal, the share of RES in the national energy mix has steadily increased in recent years. Between 2006 and 2024, electricity production from RES increased from 69 GWh to 42,208 GWh, reaching approximately 25% of the country's total electricity production in 2024 [1]. For example, regarding biogas production, the raw material potential in this sector is significant, estimated at approximately 117 million tons of organic biomass annually [2].

Effective biomass recycling is a key component of implementing sustainable development and circular economy strategies, which aim to maximize resource use through product reuse and material recovery, while minimizing waste [3]. The transformation of production systems in both the industrial and agricultural sectors should lead to the optimization of energy and raw material consumption and to the creation of closed material cycles [4].

The circular economy model builds upon the classic 3R concept (reduce, reuse, recycle), expanding it into a more comprehensive 9R framework: refuse (R0), rethink (R1), reduce (R2), reuse (R3), repair (R4), refurbish (R5), remanufacture (R6), repurpose (R7), recycle (R8), and recover (R9) [5]. These strategies enable a hierarchical approach to resource management – from preventing waste generation and reducing raw material consumption (R0–R2), through extending product lifecycles (R3–R7), to the recovery of materials and energy (R8–R9), which constitutes the final stage of resource management [5]. In the circular economy system within the agro-energy sector, agricultural biogas plants are a key component. The anaerobic fermentation of biomass produces biogas, which is used in a cogeneration system to generate electricity and heat (or in a trigeneration system to produce electricity, heat, and cooling). At the same time, the byproduct of this process is digestate, which can be used as an organic fertilizer or further processed [2]. Digestate is characterized by a high nutrient content, including nitrogen, phosphorus, and potassium; however, its direct application to soil may cause adverse changes in the soil environment. A low C/N ratio and a high content of readily available organic compounds can accelerate decomposition of organic matter, increase salinity, and disrupt soil microbial activity [6]. To increase the stability and agronomic value of digestate, biological processing methods, such as composting or vermicomposting, are increasingly used. Composting leads to the stabilization of organic matter, intensification of humification processes, and improvement of the physicochemical and biological properties of the resulting material [7]. Vermicomposting, on the other hand, involves the processing of organic matter by earthworms and soil microorganisms, resulting in a stable product with high fertilizing value [8, 9]. Compared to raw digestate, vermicompost is typically characterized by higher levels of stable humus forms, greater microbial activity, and improved nutrient availability for plants [10]. Previous research on digestate management has focused primarily on its chemical composition and fertilizing potential. Its impact on soil structural and mechanical properties, particularly on soil aggregate stability, has been analyzed much less frequently [11]. Therefore, further investigation is needed into the bioconversion processes of this material and its impact on soil properties. Dense earthworm populations play a key role in vermicomposting. One species particularly useful in this process is *Dendrobaena veneta*, which is characterized by high tolerance to fluctuating environmental conditions, high reproductive rates, and intense metabolic activity [12–15]. These characteristics make this species capable of effectively processing organic substrates with diverse physicochemical compositions [8].

The use of vermicompost improves soil properties by increasing humus content, enhancing water retention, stimulating microbial activity, and increasing the availability of minerals to plants [16-18]. The final chemical composition of vermicompost depends on the type of substrates processed, but it is typically characterized by elevated levels of macro- and micronutrients as well as humic acids that positively influence soil health and plant growth [19–21]. In the case of vermicomposting digestate, it is beneficial to mix it with other organic materials, such as horse manure. The addition of this substrate improves soil structure, increases soil porosity, and creates more favorable habitat conditions for earthworms, thereby enhancing the efficiency of this bioconversion process [22]. The resulting vermicompost is characterized by higher humus content, greater microbial activity, and improved nutrient availability for plants [19,20].

The aim of the present study involving *Dendrobaena veneta* earthworms was to determine the suitability of vermicomposting agricultural biogas plant digestate as a tool for enhancing the agronomic value of this material. The analysis included an assessment of changes in the substrate during the bioconversion process and a determination of the effect of the resulting vermicompost on the germination capacity and growth of common corn (*Zea mays*) seedlings. The results obtained allow for an assessment of vermicomposting's potential as a method for managing digestate and highlight its role in increasing the utility value of organic waste in integrated agriculture-energy systems.

MATERIALS AND METHODS

Materials

Earthworms Dendrobaena veneta (Rosa 1893)

Dendrobaena veneta belongs to a group of species that prefer environments with high concentrations of organic matter, which forms the basis for its use in vermicomposting (Figure 1). In temperate climates, this species (along with *Eisenia fetida*) is most commonly used in biodegradable waste treatment systems [8,23,24].

The body of *D. veneta* is elongated and segmented, with a cross-section resembling an octagon, slightly flattened dorsoventrally. Individuals measure 2 to 10 cm in length and 2 to 7 mm in width. Sexual maturity in this species is recognized by the presence of a clitellum, a characteristic segmental thickening involved in the reproductive process. Earthworms are hermaphroditic organisms. Mature *D. veneta* individuals possess a clitellum on segments XXV and/or XXVI–XXXII. Fertilization typically occurs 7–10 days after copulation. Cocoons are then formed, from which juvenile *D. veneta* hatch after 2–12 weeks [25]. The wide range of incubation times results from the influence of environmental factors, particularly temperature, humidity, substrate structure, and the quality and availability of food [26].

The timing of hatching in young individuals depends on factors such as substrate structure, food availability, and external conditions, including humidity and temperature [26]. High environmental tolerance and significant reproductive efficiency mean that *D. veneta* exhibits high population stability under conditions of variable technological parameters [25,27]. Given its trophic, morphological, and reproductive characteristics, *D. veneta* is a species with high application potential. In biodegradable waste processing technology, it is a key organism [27].

Digestate

Digestate (digestate mass) is a byproduct of anaerobic digestion, formed as a result of the anaerobic decomposition of organic matter in biogas plants. In physicochemical terms, it is a suspension composed of unfermented or partially decomposed feedstock residues, biomass of methanogenic microorganisms, and mineral components present in the raw material [28]. The chemical composition of the digestate depends on the type and proportions of the substrates used for fermentation. In the case of homogeneous raw materials, such as manure or corn silage, the properties of the digestate are relatively stable; however, changes in the type of biomass or its proportion can significantly affect physicochemical parameters, including macro- and micronutrient content and the presence of potential contaminants. Consequently, the quality of the digestate is directly dependent on the quality of the feedstock – high-quality substrates enable the production of valuable fertilizer, whereas contaminated material may limit its agricultural suitability. Therefore, systematic monitoring of the chemical composition and quality parameters of the digestate is necessary to ensure its safe and effective use [29,30].

Digestate contains unfermented organic compounds, microbial transformation products, and minerals. After fermentation, its pH may exceed 7.7, and the presence of organic matter upon application improves the soil's buffering capacity. Thanks to its high nutrient content, digestate is widely used in agriculture as a biofertilizer, enriching the soil with organic matter and nutrients and promoting the growth of plants and soil microorganisms [22,31]. In practice, methods for

Figure 1. Adult earthworms *Dendrobaena veneta* (Rosa 1893)

its stabilization and processing are employed, including phase separation, composting, drying, and thermal treatment, which limit odor emissions, reduce pathogens, and improve product uniformity. Table 1 presents the chemical composition of the digestate used in the experiment.

Horse manure

Horse manure is one of the oldest and most effective natural fertilizers, providing a rich source of macro- and micronutrients (including nitrogen, phosphorus, potassium, and calcium) and positively influencing the soil's physical, chemical, and biological properties, increasing organic matter content and improving water retention. In the European Union, manure with bedding is classified as biowaste intended primarily for agricultural use, although it can also be used in biogas production, composting, or as a horticultural substrate. However, improper storage can lead to environmental contamination [32]. In the experiment analyzed, manure obtained directly from the producer was used, and its characteristics are shown in Table 2.

Common corn (Zea mays L.)

Common corn (*Zea mays*), due to its high productivity and significant dry matter content, plays a significant role in the bioenergy sector. In agricultural biogas plants, it serves as a feedstock with high energy potential per unit of cultivated area, making it more efficient compared to many other energy crops [33]. The seed material used in the study was sourced from the 2024 harvest and obtained from a farm in Zbydniów (Podkarpackie Province). The seeds were fully physiologically mature. They underwent preliminary selection to ensure the homogeneity of the research material.

Experimental procedure

Vermicomposting process of the digestate

The study was conducted over 4 months in the Department of the Basis of Agriculture and Waste Management laboratory at the Faculty of Technology and Life Sciences, University of Rzeszów. The experiment was carried out using vermiculture – a concentrated population of *D. veneta* earthworms – in three distinct experimental systems (Table 3):

- S – garden soil + *D. veneta* earthworms,
- SD – garden soil with added digestate + *D. veneta* earthworms,
- SDM – garden soil with digestate and manure + *D. veneta* earthworms

Liquid digestate was applied to the surface of the vermicomposted substrate at regular monthly intervals in treatments involving mixtures containing it (SD, SDM), with the substrate in one of the treatments (SDM) additionally enriched with horse manure. Each combination was repeated three times. The experiment was conducted in vermicomposting reactors with a volume of 2 dm^3, maintained in a climate chamber under controlled conditions (temperature 20 ± 2 °C, relative humidity 60–70%). Adult *D. veneta* individuals with uniform biomass were introduced into each vermicomposting reactor, ensuring a starting density of 5 individuals·dm^{-3}. Substrate moisture was regularly monitored and maintained at an appropriate level by moistening every 5 days with an equal volume of water

Table 1. Properties of the digestate used in the study

pH in H_2O	Salinity	Content				
		$N\text{-}NO_3$	P	K	Ca	Mg
	g NaCl·dm^{-3}	mg·dm^{-3}				
7.58	9.4	640	270	720	850	430

Note: $N\text{-}NO_3$ – nitrate nitrogen; P – phosphorus; K – potassium; Ca – calcium; Mg – magnesium.

Table 2. Properties of the horse manure used in the study

Composition of horse manure used in the study (%)						pH
Dry matter	N	P	K	Ca	Mg	
25	0.54	0.29	0.90	0.43	0.16	7.2

Note: N – nitrogen; P – phosphorus; K – potassium; Ca – calcium; Mg – magnesium.

Table 3. Experimental design

Substrate variant	Garden soil*(kg)	Digestate **(ml)	Horse manure (g)
S (1, 2, 3)	2.5	-	-
SD (1, 2, 3)	2.5	200	-
SDM (1, 2, 3)	2.5	200	400

Note: *universal gardening soil by "Kronen," lightweight with a slow-release fertilizer (completely water-soluble), enriched with micronutrients (iron, boron, manganese, molybdenum, copper, zinc) and a moisture retainer that facilitates water absorption and even distribution in the substrate, pH 5.0–6.0, produced from high-quality peat, ** digestate from an agricultural biogas plant with the characteristics listed in Table 1.

(100 ml; pH 7.6, conductivity 542 µS·cm^{-1}, nitrate V 8.9 mg·dm^{-3}, Mg 15.7 mg·dm^{-3}, hardness 257 mg $CaCO_3$·dm^{-3}). Earthworm survival and biological activity were assessed by measuring population size and the number and weight of formed cocoons, enabling the determination of the effectiveness of the vermicomposting process and the impact of the applied substrate variants on earthworm development.

Physicochemical analysis of the initial substrates and vermicomposts

The macronutrient content (N, P, K, Ca, Mg) was determined in the starting substrates (S, SD, SDM) and in vermicompost. Nitrate nitrogen was determined by a colorimetric method, e.g., in a reaction with sulfanilamide and naphthylamine, while total nitrogen was determined by the Kjeldahl method. Phosphorus was determined colorimetrically using the vanadium-molybdenum method, and potassium, magnesium, and calcium were determined using atomic absorption spectrophotometry after prior mineralization of the sample in a mixture of concentrated mineral acids (HNO_3:$HClO_4$:H_2SO_4 in a 20:5:1 ratio). Carbon was determined using a Vario EL-CUBE elemental analyzer. The pH of an aqueous suspension (soil:water ratio of 1:2.5) was determined by the potentiometric method, and the salt concentration by the conductometric method [34]. The significance of differences between variants was assessed using the *Student's* t-test in Statistica.

Course of the pot experiment

In the vermicomposting process described above, the digestate was converted into vermicompost in the previously defined variants. In the next stage of the study, the resulting fertilizer materials were evaluated by analyzing their effect on the early developmental stages of common corn (*Zea mays* L.). The experiment was conducted under controlled laboratory conditions in three test variants. These included mixtures of vermicompost and potting soil at a 1:1 volume ratio, while the control sample consisted of potting soil alone.

The experiment was conducted in nine pots measuring 6 × 18 × 14 cm, filled with the appropriate substrate combinations according to the established scheme (Table 4). An equal number of seeds (24) was sown in each container. After 2 weeks, the effects of the substrate variants on selected seedling parameters were assessed, including the average number of germinated plants, average fresh biomass, and root system biomass. The experimental design thus enabled a comparative analysis of the effect of vermicompost from digestate on the growth dynamics of maize seedlings.

RESULTS AND DISCUSSION

Vermicomposting process in vermireactor

An assessment of pH changes in three substrate variants used in vermicomposters was conducted: S (soil), SD (soil with added digestate), and SDM (soil with digestate and manure). The analysis included a comparison of initial values with results obtained after a four-month vermicomposting period (Table 5). The substrate variants differed in the proportions and qualities of organic matter, which may have influenced the direction and magnitude of pH changes during the process. Initial pH values ranged from 6.5 to 6.9, corresponding to a slightly acidic to neutral pH. After 4 months of vermicomposting, a slight decrease in pH was observed across all variants; however, these changes were not statistically significant ($p > 0.05$), indicating the system's stability. The processes of mineralization and humification of organic matter lead to the formation of

Table 4. Substrate composition in the pot experiment

Variant	Substrate type*	Vermicompost /potting soil ratio**(g)	Amount of tap water***(ml)	Corn seeds****(g)
Soil S	Vermicompost from samples S 1–3	250 /250	200	5
Soil+digestate SD	Vermicompost from samples SD 1–3	250 /250	200	5
Soil+digestate +SDM manure	Vermicompost from ABC samples 1–3	250 /250	200	5

Note: * vermicompost obtained from test substrates in experiment 2.2.1, ** universal gardening soil from "Kronen," as in Table 3, *** tap water in the city of Rzeszów has the following characteristics: pH 7.7 (min: 6.5; max: 9.5), nitrate V 6.3 mg/l, nitrate III <0.05 mg/l, total organic carbon 1.50 mg/l. Municipal or local water utilities supply it via water mains. The Sanitary and Epidemiological Station fully monitors the condition and quality of this water, **** corn (*Zea mays* L.) from a farm in Zbydniów, Podkarpackie Province.

stable humic compounds [36]. Analysis of these changes allows for the assessment of the efficiency of bioconversion by earthworms, including pH stabilization and nitrogen mineralization. Changes in pH are important indicators of the vermicomposting process and the potential suitability of vermicompost for agriculture, as they influence nutrient availability to plants and the activity of soil microorganisms [35,37].

Significant differences in the salinity levels of the analyzed substrates were also observed after the vermicomposting process was completed. In the S variant (soil), the initial salinity was in the low range characteristic of mineral soils and remained at a similar level after four months, indicating the chemical stability of the system and a low content of easily soluble salts. Significantly higher salinity values were recorded in the SD variant (soil + digestate), where the initial concentration corresponded to approximately 9.6–9.7 g $NaCl \cdot dm^{-3}$. After vermicomposting was completed, this parameter decreased ($p < 0.05$), indicating the progressive stabilization of the digest under the conditions of the ongoing process. A similar trend was observed in the SDM variant (soil + digest + manure). Although the initial salinity was among the highest of the tested combinations, after four months of incubation, it decreased to a level similar to that of the SD variant.

In the final materials, a significant increase in nitrate ($N–NO_3^-$) concentration was observed compared to the initial substrates in the SD ($p < 0.05$) and SDM ($p < 0.05$) variants, indicating an intensification of organic matter mineralization processes and the transformation of organic nitrogen into mineral forms available to plants. In the S (soil) variant, changes in $N–NO_3^-$ content were minor and statistically insignificant ($p > 0.05$), which can be explained by the low content of easily degradable organic matter in the initial material. The results indicate that the presence of nitrogen-rich materials, such as digestate or manure, intensifies nitrogen transformations during vermicomposting and increases the proportion of nitrate forms in the final product [37,38].

Concerning phosphorus (P), it was found that the highest phosphorus content in the final product (vermicompost), compared to the initial substrate, was obtained in the SDM treatment (soil + digestate + manure) ($p < 0.05$). This increase can be attributed to the intensification of phosphorus-containing organic matter decomposition and to increased activity of microorganisms involved in the mineralization of phosphorus compounds.

An increase in the content of available forms of phosphorus during vermicomposting is a phenomenon frequently observed in materials rich in organic matter, such as manure or digestate, where the mineralization of organic forms of P and the release of orthophosphates occur [18,35]. This process is further aided by the activity of earthworms, which, through the fragmentation and mixing of the substrate and the transformations in their digestive tract, increase the proportion of available phosphorus forms in vermicompost [8,24].

In the conducted studies, the total content of P, K, Ca, and Mg in the analyzed substrates was determined, with higher concentrations generally observed after the completion of the vermicomposting process compared to the initial material. This phenomenon can be explained by the relative concentration of elements resulting from a reduction in substrate mass during the mineralization of organic matter and the emission of gaseous products of carbon and hydrogen oxidation.

Table 5. Selected characteristics of substrates and the final material produced in vermicomposters

Selected characteristics		Characterized substrate	S	SD	SDM
pH		Starting material	6.5±0.6 [a]	6.7±0.3 [a]	6.9±0.3 [a]
		Final substrate with vermicompost	6.4±0.6 [a]	6.6±0.6 [a]	6.8±0.5 [a]
Salinity (NaCl g·dm^{-3})		Starting material	1.60.4 [a]	9.6±0.5 [a]	9.7±0.7 [a]
		Final substrate with vermicompost	0.7±0.2 [a]	5.1±0.4 [b]	5.4±0.5 [b]
N-NO_3	mg·dm^{-3}	Starting material	568±26 [a]	943±46 [a]	926±94 [a]
		Final substrate with vermicompost	668±42 [a]	2170±74 [b]	2158±98 [b]
P		Starting material	684±33 [a]	603±66 [a]	628±53 [a]
		Final substrate with vermicompost	616±63 [a]	679±39 [a]	895±70 [b]
K		Starting material	968±39 [a]	1661±32 [a]	1643±44 [a]
		Final substrate with vermicompost	1150±45 [a]	3516±58 [b]	4360±71 [b]
Ca		Starting material	740±56 [a]	1194±43 [a]	1288±56 [a]
		Final substrate with vermicompost	834±37 [a]	2499±91 [b]	2623±56 [b]
Mg		Starting material	263±5 [a]	301±18 [a]	333±24 [a]
		Final substrate with vermicompost	319±8 [a]	762±23 [b]	850±41 [b]
C:N		Starting material	23±1 [a]	26.3±1 [a]	27±4 [a]
		Final substrate with 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.

During the process, part of the carbon is also incorporated into the biomass of earthworms (*D. veneta*), while other elements contribute to a lesser extent to the formation of their tissues, thereby increasing their concentration in the remaining substrate mass. Additionally, the intense activity of microorganisms and earthworms decomposes complex organic compounds and gradually releases mineral nutrients. As a result, the final material is characterized by a higher concentration of macronutrients and greater fertilizing value. A similar increase in macronutrient content resulting from the degradation of organic matter during the vermicomposting of organic waste has also been reported in other studies, indicating the widespread nature of this phenomenon in bioconversion processes involving earthworms [39,40].

A decrease in the C/N ratio is observed across all three substrates, a typical indicator of oxidation and mineralization of organic carbon, and a relative increase in nitrogen availability, indicating the progress of organic matter decomposition. The C/N ratio is one of the most commonly used indicators for assessing the maturity and stability of vermicompost, as it reflects the course of organic matter mineralization processes and the degree of stabilization of the processed material. During the vermicomposting process, this indicator gradually decreases, mainly due to the loss of carbon as CO_2 during the intense activity of microorganisms and earthworms, and to a relative increase in the nitrogen content of the final material. A decrease in the C/N ratio compared to the initial material indicates progressive humification and stabilization of organic matter [36]. The intensity of these transformations is closely related to the biological activity of the environment, encompassing both microorganisms and earthworms, whose living conditions determine the rate of organic matter transformation.

Domínguez and Edwards [8] emphasize that the vermicomposting process results from the synergy among microflora activity, earthworm bioturbation, and digestive processes, leading to the mineralization of nutrients and an increase in their concentration in the final material. In turn, Arancon et al. [41] demonstrated that the mineralization of organic matter during vermicomposting increases the content of macronutrients, including Ca and Mg, thereby enhancing the fertilizing value of the product.

The results indicate that the SDM variant provided the most favorable conditions for *D. veneta* development, reflected in the highest concentrations of the analyzed macronutrients in this substrate. A significant increase in potassium, calcium, and magnesium concentrations in the SD ($p < 0.05$) and SDM ($p < 0.05$) variants indicates improved soil physicochemical properties and the beneficial effect of adding digestate and manure on soil macronutrient content. The results indicate that the addition of digestate and manure to the base substrate (S) significantly alters its chemical properties, in a manner beneficial to plants, particularly in nitrogen, phosphorus, potassium, calcium, and magnesium content. The presence of easily degradable organic matter intensified mineralization processes under conditions of *D. veneta* activity, thereby increasing the substrate's macroelement content.

The highest fertilizing value was obtained in the SDM variant (soil + digestate + manure), in which the highest concentrations of macronutrients, favorable pH stabilization, and the most intense organic matter transformation were observed. The SD variant (soil + digestate) also showed a marked improvement in chemical parameters, though to a lesser extent than with the manure combination. The S variant showed the least dynamic changes, confirming that the use of organic components in a system involving *D. veneta* significantly improves the quality of the final vermicompost and its potential suitability for corn cultivation. The results of the physicochemical property analysis of the tested substrates are summarized in Table 5.

Digestate can be a valuable source of macronutrients essential for plant growth, particularly nitrogen, phosphorus, and potassium, which makes it suitable for use as an organic or organic-mineral fertilizer [42,43]. The literature emphasizes that digestate is characterized by a significant proportion of nitrogen in mineral forms and the presence of available phosphorus and potassium, which increases its fertilizing efficiency and allows for partial replacement of mineral fertilizers in agricultural systems [10].

The application of digestate to soil can improve its agrochemical properties, including increasing organic matter content and stimulating the activity of soil microorganisms, thereby promoting the intensification of nutrient cycling [44]. At the same time, the literature indicates that fresh digestate, without prior stabilization under aerobic conditions (e.g., through composting or vermicomposting), may exhibit properties that limit its direct agricultural application [39,45].

High levels of ammonium nitrogen can lead to temporary phytotoxicity and nitrogen losses through ammonia emissions, while increased moisture content hinders storage and uniform field application. Furthermore, the digestate may contain undesirable substances such as heavy metals, PAHs, drug residues, or pathogens, depending on the type of input substrates [42]. In light of the above, the experiment also assessed the population parameters of *D. veneta* earthworms, which served a dual function: as an element of vermicomposting biotechnology and as a bioindicator of the quality of the tested substrates. The effect of the substrate combinations on the number of individuals was analyzed, and the dynamics of the earthworm population were monitored (Figure 2), allowing assessment of both the organisms' tolerance to substrate properties with added digestate and the degree of population stabilization during the process.

At the first control date (b), the *D. veneta* population remained at a level close to the initial values in the S (soil) and SDM (soil + manure + digestate) variants. At the second monitoring date (c), there was a marked increase in earthworm population abundance in the SDM variant, whereas only a moderate upward trend was observed in the S and SD variants. The final check (d), conducted after four months, showed a statistically significant increase in population size in the SDM variant ($p < 0.05$). In this variant, the number of individuals was more than five times higher than in the S variant and greater than in the SD variant, indicating the most favorable environmental conditions in the combination of soil, digestate, and manure.

The observed population dynamics were most likely the result of the synergistic interaction of manure and digestate under substrate conditions with lower nutrient content. Manure serves as a source of easily biodegradable organic carbon fractions, improves the physical structure of the substrate (porosity, aeration, water retention), and promotes the development of active microflora, which plays a key role in organic matter transformation processes [41]. In turn, digestate contributes significant amounts of nitrogen – mainly in mineral forms – as well as phosphorus, potassium, and other macronutrients, thereby increasing nutrient availability in the soil system [38].

The combined application of these components promotes a more favorable C/N ratio, considered one of the key factors determining the growth and reproduction rates of compost earthworms [24]. At the same time, the presence of

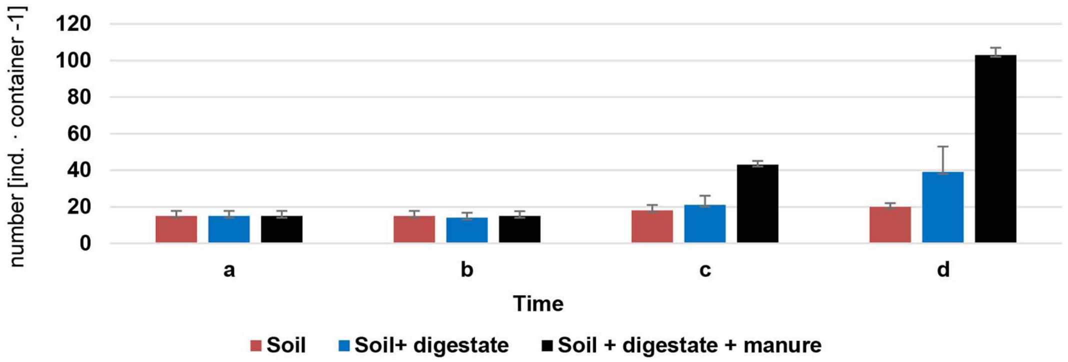

Figure 2. Average total abundance of *D. veneta* earthworms depending on the substrate composition in the vermireactor

organic matter at varying stages of decomposition may limit local increases in ammonia and mineral salt concentrations by immobilizing them within the structures of developing humus, which, in the SD variant (without manure addition), may have periodically limited the reproductive activity of organisms. The results confirm that despite the high environmental tolerance of *D. veneta* earthworms, their growth rate is strongly dependent on the quality and diversity of available food and on the microbial activity of the substrate [8,41]. In the study, the SDM experimental variant proved to be the most effective substrate for vermicomposting, promoting rapid population growth, accelerating processing of organic biomass, and stabilizing the process under variable moisture content and substrate structure. The advantage of this variant stemmed from the complementary actions of its components: manure provided readily available carbon and improved the substrate's physical properties, while digestate enriched it with assimilable forms of nitrogen and macronutrients. This combination increased microbial activity, accelerated the mineralization of organic matter, and supported the survival and reproduction *of D. veneta*. The higher population density in the SDM variant compared to S and SD confirms that substrate quality and diversity are crucial for the growth dynamics of compost earthworms, a finding supported by the literature [21,39]. Consequently, the SDM variant can be considered optimal under the conditions of this experiment, both in terms of bioconversion efficiency and the population growth potential of *D. veneta*.

Crutchik et al. [46] evaluated the effects of applying two digestate doses (30% and 60% v/v) on the population dynamics of *Eisenia fetida* earthworms, the maturity of the final vermicompost, and changes in the microflora structure. The results showed that adding digestate increased earthworm abundance and biomass without hindering the vermicomposting process. The highest population growth, up to 168%, was recorded in the variant with a 60% digestate dose. In all variants, mature compost meeting quality criteria was obtained. The effect of the digestate on the abundance of immature individuals was also examined. After 109 days of the experiment, their number increased 3.6-fold in the variant with 30% digestate, 2.4-fold in the variant with 60% digestate, and 2.3-fold in the control variant (using water instead of digestate). Kowalski et al. [47] observed in their experiments that adding digestate to the substrate affected the abundance of adult *E. fetida*. In the control group, where digestate was not used, the average number of adult earthworms per 1 kg of substrate was 50. In contrast, in the experimental groups where digestate was added at 10%, 20%, and 30%, the number of adult earthworms increased to 65, 75, and 80 per 1 kg of substrate, respectively.

As part of the experiment conducted with *D. veneta*, the effect of the substrate variants used on earthworm reproductive parameters was also evaluated. The key indicator of reproductive efficiency was the number of cocoons produced and their biomass, which constitute a direct measure of the population's reproductive activity (Figure 3).

Analysis of reproductive parameters confirmed the pattern previously observed regarding population size. The highest number of cocoons laid was recorded in the SDM variant (soil + manure + digestate), particularly during the second observation period (b), where the average number reached its highest values (35 ± 15 cocoons·container^{-1}). At the same observation date, the S variant (soil) and the SD variant (soil + digestate) were characterized by a significantly lower number of cocoons (3.5 ± 4 and 4.5 ± 7, respectively), although these differences did not always reach the level of statistical significance. In subsequent time points (c and d), the number of cocoons in the SDM variant decreased, but remained higher than in the other substrate combinations. In the S and SD variants, moderate but stable reproductive activity was observed, without any marked sudden changes. Cocoons are a key element of the earthworm life cycle, reflecting their reproductive potential and ability to adapt to environmental conditions [27]. The literature emphasizes that both the number and biomass of cocoons produced by compost earthworms depend on the quality and type of the processed substrate [15,21]. The experiment also revealed significant differences in the biomass of the cocoons produced depending on the substrate composition, indicating that not only the number but also the mass parameters of the reproductive structures are sensitive to the chemical and biological properties of the vermicomposting environment (Figure 3).

Analysis of cocoon biomass confirmed a clear variation in the reproductive response of earthworms depending on the composition of the vermicomposted substrate. The highest biomass values were recorded in the SDM variant (soil + manure + digestate), particularly during the second observation period (b), where the maximum level was reached (1.40 ± 0.02 g·container^{-1}). At the same time, this variant showed the greatest variability in results, indicating the dynamic nature of reproductive processes during the initial phase of intensive population growth. In the S variant (soil), cocoon biomass remained at a low, relatively stable level at all observation dates, not exceeding 0.1 ± 0.01 g·container^{-1}. Similarly, in the SD variant (soil + digestate), these values were significantly lower than in the manure combination, and only slight fluctuations were observed at subsequent time points. In the third (c) and fourth (d) monitoring periods, cocoon biomass in the SDM variant decreased significantly compared to the maximum from period b, but remained comparable to the other variants. This decline can be attributed to the transition of part of the population into the hatching phase of juveniles and a shift in energy allocation from cocoon production to the growth of juvenile stages. The results indicate that the combination of soil, digestate, and manure in the vermicomposters created the most favorable conditions for the intensive reproduction *of D. veneta*, as confirmed by both the highest number and biomass of cocoons laid in this variant. The number and biomass of cocoons laid by earthworms depend on many abiotic factors, such as temperature, humidity, substrate composition, and biotic factors (e.g., population density) [21,48].

Kostecka and Kaniuczak [48] conducted a vermicomposting process over four months. The experiment used two variants: duckweed and duckweed mixed with manure in a 1:1 ratio. The study utilized the compost earthworm *E. fetida*. The results indicated that the variant with added manure had a beneficial effect on the biomass of cocoons laid by earthworms, suggesting better conditions for development and reproduction compared to the single-component variant.

Cocoons are a fundamental element of the earthworm life cycle, serving as an indicator of their adaptive capacity and reproductive potential under specific environmental conditions. The quantitative and mass parameters of the cocoons thus reflect the condition of the population and the suitability of the food substrate used in the vermireactor.

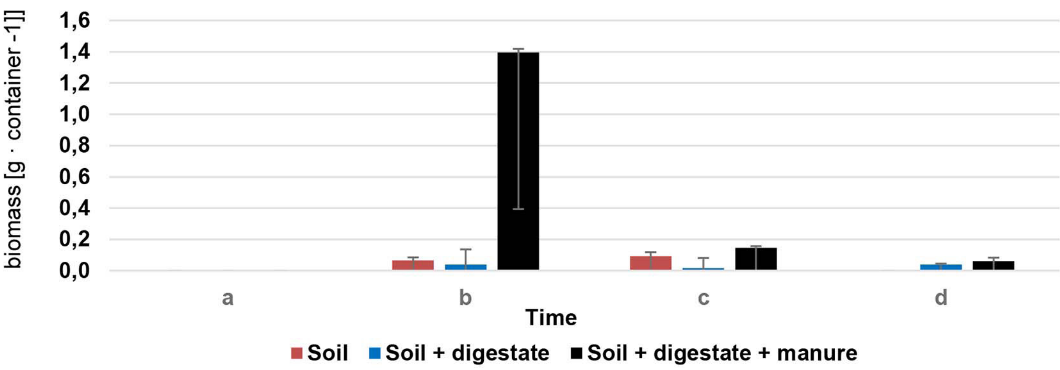

Figure 3. Average biomass of *D. veneta* cocoons depending on the composition of the vermicomposted substrate

Table 6. Average number of stems, aboveground biomass, and root system biomass of maize (*Zea mays*) in individual experimental treatments

Substrate treatment	Emergence characteristics		
	Total number of stalks [pcs.]	Total stem biomass [g]	Average root biomass [g]
Soil (S)	27.00 ± 2.51[a]	23.20 ± 1.48[a]	19.21 ± 5.05[a]
Soil + Post-fermentation residue (SD)	28.00 ± 1.52[a]	34.21 ± 3.46[b]	24.03 ± 5.28[a]
Soil + Post-ferment + manure (SDM)	28.21 ± 2.43[a]	36.21 ± 2.43[b]	39.06 ± 6.09[b]

Note: [*] "Kronen" universal potting soil, as in Table 3, aa, bb – no statistically significant differences, ab – statistically significant differences.

The results confirm that both *D. veneta* and *E. fetida* show a clear preference for vermicomposters with a substrate mix containing manure, which provides more favorable trophic and physical conditions for the development and reproduction of earthworm populations and, consequently, for the composition of the vermicompost produced.

Effect of substrates containing vermicompost derived from digestate on the germination and emergence of maize seedlings (*Zea mays*)

No significant differences in the number of common corn (*Zea mays*) seedlings were observed among the analyzed substrate variants (Table 6). However, significant differences were observed in the seedlings' aboveground biomass. The variants with added digestate (SD) and digestate plus manure (SDM) showed significantly higher total stem biomass ($p<0.05$) than the control substrate (S). An analysis of the biomass of *Zea mays* maize seedlings grown on the tested substrates (Table 5) indicates that the content of available macronutrients was higher in the variants with organic amendments, particularly in the SDM combination, confirming the high agronomic value of the vermicompost obtained. It indicates that the applied organic amendments positively influenced the growth and development of the plants' aboveground parts. The greatest differences were observed in root system biomass. The SDM variant resulted in the highest average root biomass ($p < 0.05$), and the results suggest that post-ferment with manure promoted the intensification of root system development, which may further translate into better nutrient and water utilization by growing plants.

Similarly, Piątek and Bartkowiak [49] conducted a study to assess the effect of digestate on winter rapeseed emergence. In the first treatment, corn silage and distillers' grains were used as substrates for fermentation, while in the second, corn silage and swine manure were used. The application of both digestates had a beneficial effect on plant growth, indicating increased mineral uptake efficiency and improved nutrient availability in the soil. Research by Lee et al. [50], concerning the effect of applying pure digestate and digestate with added biochar in the cultivation of switchgrass (*Panicum virgatum* L.), confirmed the positive impact of these materials on plant growth. In both variants, the biomass obtained was comparable, and both the digestate alone and the digestate enriched with biochar improved the growth of the tested plant.

The results obtained are consistent with a broader body of research confirming the positive impact of organic fertilizers – vermicompost – on plant development and soil properties. Similar conclusions were presented by Hussain and Abbasi [51], who demonstrated that the application of vermicompost positively modifies soil structure and increases its productivity throughout the entire plant growth cycle. Their studies noted improvements in growth parameters and plant health for species such as tomato (*Solanum lycopersicum*), lettuce (*Lactuca sativa*), cucumber (*Cucumis sativus*), pepper (*Capsicum* spp.), and bean (*Phaseolus vulgaris*).

CONCLUSIONS

The results indicate that the key factor determining the effectiveness of the vermicomposting process is the appropriate substrate composition in the vermireactor. The most favorable biological and chemical effects were observed with the SDM variant (soil + digestate + horse manure), which maintained stable environmental conditions and a balanced C:N ratio. Under these conditions, the highest abundance of *D. veneta* individuals, the highest production of cocoon numbers and biomass, as well as a marked improvement in the quality parameters of the produced vermicomposts, were recorded. The lumpy structure of the vermicomposts confirmed their advanced degree of humification and the effectiveness of organic matter bioconversion by earthworms. During the bioprocess described, there was a concentration of macronutrients (N, P, K, Ca, Mg) resulting from the mineralization of organic matter and a reduction in its mass. At the same time, pH stabilization and a decrease in salinity were observed in the variants containing digestate, indicating effective substrate maturation and reduced potential stressors for soil organisms. It means that vermicomposting is an effective method for stabilizing digestate prior to its agricultural use. Analysis of plant responses showed that vermicompost derived from digestate, especially when combined with manure, had a beneficial effect on the initial growth of *Zea mays* (corn). Although the number of stems did not differ significantly between treatments, the increased biomass of the aboveground parts and the root system indicates a potential improvement in nutrient availability for growing corn. The effect was particularly pronounced in terms of root development, confirming the high fertilizing value of the resulting product.

From a circular economy perspective, the vermicomposting of digestate enables its transformation from a problematic waste material into a stable, valuable organic fertilizer. The appropriate combination of input components in the vermireactors reduces the risk of nitrogen loss and minimizes its potential phytotoxicity. The decline in earthworm reproduction observed in the final phase of the experiment should be interpreted as a natural consequence of food resource depletion in a closed system, which can be mitigated through scheduled substrate replenishment. The results of the experiment confirm that co-processing digestate with manure (in this case, horse manure) in a vermicomposting system is an environmentally sound and economically viable solution that increases the added value of biowaste streams. Further optimization of component ratios and research on the synergistic combination of digestate with other organic fractions may further increase the efficiency and scalability of this biotechnology.

REFERENCES

1. Polish Electricity Transmission System Operator. Report 2024 Polish Power System. available online: https://www.pse.pl/ dane-systemowe/funkcjonowanie-kse/raporty-roczne-z-funkcjonowania-kse-za-rok/raporty-za-rok-2024#r6_3
2. Łukomska A., Witaszek K., Dach J. Current state of development of demand-driven biogas plants in Poland. Procesess, 2025; 13: 2369. https://doi.org/10.3390/pr13082369
3. De Melo T.A.C., de Oliveira M.A., de Sousa S.R.G., Vieiria R.K, Amaral T.S. Circular economy public policies: A systematic literature review. Procedia Computer Science, 2022; 204(C): 652–662. https://doi.org/10.1016/j.procs.2022.08.079
4. Chennak A., Giannakas K., Awado T. On the economics of the transition to a circular economy. Circular Economy and Sustainability, 2024; 4: 30007–3023. https://doi.org/10.1007/s43615-023-00297-8
5. Rahla K.M., Mateus R., Bragança L. Selection criteria for building materials and components in Line with the circular economy principles in the built environment - A review of current trends. Infrastructures, 2021; 6: 49. https:// doi.org/10.3390/infrastructures6040049
6. Möller K., Müller T. Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. Engineering in Life Sciences, 2012; 12(3): 242–257. https://doi.org/10.1002/elsc.201100085
7. Tambone F., Genevini P., D'Imporzano G., Adani F. Assessing amendment properties of digestate by studying the organic matter composition and the degree of biological stability during the anaerobic digestion of the organic fraction of MSW. Bioresource Technology, 2010; 101(2): 251–258. https://doi.org/10.1016/j.biortech.2009.02.012
8. Domínguez J., Edwards C. A. Biology and ecology of earthworm species used for vermicomposting. In: Edwards C. A., Arancon N. Q., Sherman R. L. (Eds.), Vermiculture Technology: earthworms, organic waste and environmental management. CRC Press, Boca Raton, 2011; 27–40.
9. Cucina M., Castro L., Font Pomarol J., Escalante H., Munoz-Munoz A., Ferner J., Garfi M. Wermifiltration as a green solution to promote digestate reuse in agriculture in smal- scale farms. Journal of Environmental Management, 2024; 368: 122164. https://doi.org/10.1016/j.jenvman.2024.122164
10. Alburquerque J.A., de la Fuente C., Campoy M., Carrasco L., Nájera I., Baixauli C., Caravaca F., Roldán A., Cegarra J., Bernal M.P. Agricultural use of digestate for horticultural crop production and improvement of soil properties. European Journal of Agronomy, 2012; 43: 119–128. https://doi.org/10.1016/j.eja.2012.06.001

11. Gryta A., Boguta P., Józefaciuk G., Skic K. Utilization of post-fermentation sludge as a soil structure and strenght conditioner. Scientific Reports, 2025; 15: 38982. https://doi.org/10.1038/s41598-025-22871
12. Kostecka J. Badania nad wermikompostowaniem odpadów organicznych. Zeszyty Naukowe Akademii Rolniczej w Krakowie. Rozprawy, 2000; 268: 1–88.
13. Garczyńska M., Pączka G., Wirkus K., Podolak A., Mazur-Pączka A., Szura R., Bartkowska I., Kostecka J. Vermicomposting of post-harvest maize waste. Annual Set of Enviromental Protection, 2018; 20: 358–374.
14. Garczyńska M., Kostecka J., Kaniuczak J. Effect of fertilization with the sheep manure vermicompost on the yield of sweet potatoes and selected properties of soil developed from loess. Journal of Ecological Engineering, 2020; 21(5): 27–33. https://doi.org/10.12911/22998993/122183
15. Garczyńska M., Kostecka J., Pączka G., Hajduk E., Mazur-Pączka A., Butt R.K. Properties of vermicomposts derived from cameroon sheep dung. Applied Science, 2020; 10(15): 5048. https://doi.org/10.3390/app10155048
16. Atiyeh R. M., Domínguez J., Subler S., Edwards C. A. Changes in biochemical properties of cow manure during processing by earthworms (*Eisenia andrei*) and effects on seedling growth. Pedobiologia, 2000; 44(6): 709–724.
17. Edwards C. A., Arancon N. Q. Interactions among organic matter, earthworms, and microorganisms in promoting plant growth. In: Magdoff F., Weil R. R. (Eds.), Soil Organic Matter in Sustainable Agriculture. CRC Press, 2004; 327–376.
18. Lazcano C., Domínguez J. The use of vermicompost in sustainable agriculture: impact on plant growth and soil fertility. Soil Nutrients, 2011; 10(1): 1–23.
19. Arancon N. Q., Lee S., Edward C. A., Atiyeh R. Effects of humic acids derived from cattle, food and paper-waste vermicomposts on growth of greenhouse plants. Pedobiologia, 2003; 47: 741–744.
20. Usmani Z., Kumar V., Gupta P., Gupta G., Rani R., Chandra A. Enhanced soil fertility, plant growth promotionand microbial enzymatic activities of vermicomposted fly ash. Scientific Reports, 2019; 9: 10455, 1–16.
21. Pączka G., Mazur-Pączka A., Garczyńska M., Podolak A., Szura R., Butt K., Kostecka J. Using earthworms *Eisenia fetida* (Sav.) for utilization of expansive litoral plants biomass. Applied Sciences, 2019; 9: 3635, 1–13. https:// doi.org/10.3390/app9173635
22. Sapp M., Harrison, M., Hany U., Harding S. Potential of digestate as a novel substrate for composting. Waste Management, 2015; 43: 85–95.
23. Edwards C.A., Bohlen P.J. Biology and Ecology of Earthworms. Chapman & Hall, London, 1996; 46.
24. Domínguez J., Edwards C. A. *Relationships between composting and vermicomposting: Relative values of the products.* In: C. A. Edwards et al. (Eds.), Vermiculture Technology: Earthworms, Organic Wastes, and Environmental Management. CRC Press, Boca Raton, 2011; 1–14.
25. Kasprzak K. Skąposzczety glebowe III. Rodzina Dżdżownic (Lumbricidae). Klucz do oznaczeń bezkręgowców Polski, 1986; 187.
26. Kostecka J. Poradnik Hodowcy dżdżownic. Akademia Rolnicza im. H. Kołłątaja w Krakowie, Filia w Rzeszowie, 1994; 1–40.
27. Dominguez J. Earthworms and Vermicomposting. Earthworms. The Ecological Engineers of Soil, 2018; 5: 63–77.
28. Kowalczyk-Juśko A., Szymańska M. Wartość nawozowa pofermentu z biogazowni rolniczych. Roczniki Naukowe SERiA, 2015; 17(4): 122–128.
29. Logan M., Visvanathan C. Management strategies for anaerobic digestate of organic fraction of municipal solid waste: Current status and future prospects. Waste Management & Research, 2019; 37(1): 27–39.
30. Szubska-Włodarczyk N. Produkcja biogazu z odpadów produkcji zwierzęcej jako wsparcie dla neutralności klimatycznej w ujęciu regionalnym - przykład Wielkopolski. Rozwój Regionalny i Polityka Regionalna, 2024; 72: 193–211.
31. Cybulska K., Czekała W., Dach J. The influence of digestate from biogas plants on soil and plant environment. Journal of Water and Land Development, 2015; 27: 3–10.
32. Lin Y.H., Chen T.Y., Chang Ch.H., Lin T.C., Lee Y.J., Lin M.J., Lin J.H. Shorten the producing s of horse manure to fermented compost and appropriate fertilization on crops. Journal of Agricultural Biotechnology and Sustainability Development, 2021; 13(11): 1–11. https://doi.org 10.5897/JABSD2020.0381
33. Duan P. Response of maize genotypes with different nitrogen use efficiency to low nitrogen stresses. Acta Ecologica Sinica, 2019; 39(1): 77–80. https://doi.org/10.1016/j.chnaes.2018.05.005
34. MAFF. The Analysis of Agricultural Materials: A Manual of the Analytical Methods Used by the Agricultural Development and Advisory Service (ADAS), HMSO, London, UK, 1981.
35. Gómez-Brandón M., Fernández-Delgrado J., Zangerle M., Insam H. Effects of digestate on soil chemical and microbiological properties. A. comparative study with compost and vermicompost, 2016; 302: 267–274. https://doi.org/10.1016/j.jhazmat.2015.09.067
36. Sharma K., Garg V.K. Comparative analysis of vermicompost quality produced from rice straw and paper waste employing earthworm. Bioresource Technology, 2018; 250: 708–715. https://doi.org/10.1016/j.biortech.2017.11.101

37. Hanc A., Dreslova. Effect of composting and vermicomposting on properties of particle size fractions. Bioresource Technology, 2016; 217: 186–189. https://doi.org/ 10.1016/j.biortech.2016.02.058
38. Manu M.K., Dongyi Li., Liwen Luo, Juan Z., Varjani S., Wong J.W.C. A review on nitrogen dynamics and mitigation strategies of food waste digestate composting. Bioresource Technology, 2021; 334: 125032. https://doi.org/10.1016/j.biortech.2021.125032
39. Suthar S. Vermicomposting of vegetable-market solid waste using *Eisenia fetida*: impact of bulking material on earthworm growth and decomposition rate. Ecological Engineering, 2009; 35(5): 914–920. https://doi.org/10.1016/j.ecoleng.2008.12.019
40. Rini J., Deepthi M.P., Saminathan K., Narendhirakannan R.T., Karmeham N., Kathireswari P. Nutrient recovery and vermicompost production from livestock solid wastes with epigeic earthworms. Bioresource Technology, 2020; 313: 123690. https://doi.org/10.1016/j.biortech.2020.123690
41. Arancon N.Q., Edwards C.A., Bierman P. Influences of vermicomposts on field strawberries: Part 1. Effects on growth and yields. Bioresource Technology, 2004; 93: 145–153. https://doi.org/10.1016j.biortech.2003.10.014
42. Tambone F., Scaglia B., D'Imporzano G., Schievano A., Orzi V., Salati S., Adani F. Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost. Chemosphere, 2010; 81(5): 577–583. https://doi.org/10.1016/j.chemosphere.2010.08.034
43. Abubaker J., Risberg K., Pell M. Biogas residues as fertilisers – Effects on wheat growth and soil microbial activities. Appl. Energy, 2013; 99: 126–134. https://doi.org/10.1016/j.apenergy.2012.04.050
44. Van Midden Ch., Harris J., Shaw L., Sizmur T., Pawlett M. The impact of anaerobic digestate on soil life: A review. Applied Soil Ecology, 2023; 191: 105066. https://doi.org/10.1016/j.apsoil.2023.105066
45. Krishnasamy K., Nair J., Bell R. Evaluation of anaerobic digestate as a substrate for vermicomposting. International Journal of Environment and Waste Management, 2014; 14(2): 149–162. https://doi.org/10.1504/IJEWM.2014.064084
46. Crutchik D., Rodríguez-Valdecantos G., Bustos G., Bravo J., González B., Pabón-Pereira C. Vermiproductivity, maturation and microbiological changes derived from the use of liquid anaerobic digestate during the vermicomposting of market waste. Water Science and Technology, 2020; 82(9): 1781–1794. https://doi.org/10.2166/wst.2020.427
47. Kowalski A., Wiśniewski J., Zielińska M. Wpływ pofermentu na rozwój i reprodukcję dżdżownic *Eisenia fetida*. Roczniki Nauk Rolniczych, 2020; 45(2): 123–130.
48. Kostecka J., Kaniuczak J. Vermicomposting of duckweed (*Lemna minor L.*) biomass by *Eisenia fetida* (Sav.) earthworm. Journal of Elementology, 2008; 13(4): 571–579.
49. Piątek M., Bartkowiak A. Ocena wybranych właściwości fizykochemicznych gleby nawożonej masą pofermentacyjną. Woda-Środowisko-Obszary wiejskie, 2019; 1(65): 55–66.
50. Lee M. S., Urgun-Demirtas M., Shen Y., Zumpf C., Anderson E. K., Rayburn A. L., Lee D. K. Effect of digestate and digestate supplemented with biochar on switch grass growth and chemical composition. Biomass and Bioenergy, 2021; 144: 105928.
51. Hussain N., Abbasi S.A. Efficacy of the vermicomposts of different organic wastes as clean fertilizers: State of the Art. Sustainability, 2018; 10(1205): 1–63. https://doi.org/10.3390/su10041205