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Development of a Comprehensive Technology for Processing Consumer Waste

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Abstract: The purpose of the study was to examine vermitechnology as an effective method of waste recycling. The study used theoretical and empirical methods, including experiments, to explore vermitechnology in Kazakhstan, consumer waste processing, and fertilizer usage in the agricultural sector. In the study analyses of the processing of organic waste (chicken, cattle, food waste) through California worms were obtained. Analyses of the trace element composition were obtained. In the course of the study, the terms of processing of various types of waste, the specific features of the worms' vital activity and habits, the adaptation of worms to new types of food additives and general monitoring of the course of the processing process were determined. Special attention is paid to the secondary product of processing – biohumus, which is an intensive high-quality organic fertiliser. In this study, it was proven that vermicomposting organic waste is an optimal, eco-friendly recycling process, generating valuable components for further consumption. The paper substantiates that vermicomposting technology allows creating a mechanism for the biochemical circulation of substances, organising an almost waste-free, closed cycle of agricultural production. The study has high practical importance, its results can be successfully applied in the development and implementation of integrated eco-technologies for waste processing, and in the process of optimising agricultural processes.

Keywords: California worms; organic waste, chicken manure; cattle manure; vermicompost

1. Introduction

Every year humanity suffers the loss of food and waste from one-third to half of all food produced. Notably, losses occur at all stages of the chain, from the production to the supply of food or the chain of creation of surplus value. According to data from the Food and Agriculture Organisation of the United Nations (FAO), on average, one person living in Europe or North America generates about 95-115 kg of waste per year at the consumption stage, while in Sub-Saharan Africa – about 6-11 kg per year[1)]. The rapid growth of consumption waste is already one of the important environmental problems that require effective methods of solving. Despite the existence of various methods of recycling consumer waste, researchers from different countries are striving to improve these technologies and achieve the greatest efficiency of processes. State support of agriculture is typical for most countries of the world, experts distinguish various goals and forms. Countries with highly developed industrial economies strive to support the competitiveness of food products and sustainable rural areas through subsidies and benefits. In transitional economies, the objectives are to restructure and modernize production to meet global standards and ensure affordable food supply for the countries.

The processing of organic waste, in particular, agricultural waste, for the production of vermicompost, fertilisers, and bio-feeds is getting traction. In Kazakhstan, the programme "Agribusiness 2020" was developed to support and expand the agro-industrial complex, as part of the implementation of the Strategy "Kazakhstan-2050"[2)]. The program's objectives include improving agrochemical

services, information support, variety testing of crops, reclamation of irrigated lands, promoting organic product production, and facilitating international cooperation in the agro-industrial complex. Its overall aim is to increase the efficiency and sustainability of agriculture.

Vermitechnology, a highly effective method of ensuring the sustainability of local ecosystems, is a modern effective area in the field of consumer waste disposal and optimisation of agricultural processes. Indeed, these measures involve cultivating compost worms on various substrates in specific environmental conditions, to produce and accumulate their excreta (vermicompost) and biomass. The use of vermitechnology on a scientific basis is a serious alternative to existing technologies for the disposal of all types of organic waste.

Many papers are devoted to the problems of the introduction of vermitechnology as a set of measures and the search for solutions to problematic issues arising during operation, in particular, by researchers Sh. Singh et al.[3], T.M. Korsunova et al.[4], K. Singh et al.[5]. They consider vermitechnology as a multifaceted subject of research, focusing on the main function of biotechnology – the efficient waste-free processing of organic matter. Therewith, modern researchers K. Anand[6], R. Nogales et al.[7], N. Karmegam[8] conclude that no less important are other results of the introduction of vermitechnology – biohumification, improvement of the ecological situation, and the opportunities that subsequently open up for organic agricultural production. K. Samal[9] and R. Nogales et al.[7] consider the need for parallel implementation of an effective environmental monitoring system to optimise the process, conduct a timely diagnosis of problems, and determine ecological-economic efficiency while regulating the influence of the human factor on the process.

Vermicomposting and vermicultivation offer a comprehensive solution for optimizing organic waste disposal and recycling. This will improve the environmental situation and produce a highly effective organic fertilizer, biohumus, essential for restoring soil fertility, increasing productivity, and promoting eco-friendly agricultural products. In addition, another positive consequence of vermitechnology is the production of a substantial amount of feed protein in the form of worm biomass, which is necessary for animal husbandry and in the production of compound feeds. In general, all these aspects will allow purposefully implementing a programme of greening agricultural production, while solving the problem of waste-free disposal of consumer products. Currently, vermitechnologies in Kazakhstan are classified as innovative areas of development of environmental and agricultural industries. Their prospects leave no doubt, enabling the count on additional investment opportunities both through internal economic and environmental programmes and international projects.

The study aimed to assess the effectiveness of vermitechnology in eco-friendly organic waste recycling through California worms, analysing trace elements, studying worm behaviour, and highlighting valuable biohumus production as a secondary outcome. The novelty of the study lies in its comprehensive examination of vermitechnology as an effective waste recycling method, specifically focusing on the processing of various organic waste types through California worms.

2. Literature Review

A study by Sh. Singh et al.[3], present the method of anaerobic decomposition of consumer waste processing and its technological features. Today, there are various methods of processing food waste in the world, among them are methods of anaerobic decomposition to produce biogas and vermicomposting to produce vermicompost. Anaerobic decomposition is a biotechnological method of processing food waste by using microorganisms of the methanogenic community. The anaerobic decomposition method consists of several stages:

1. First of all, the mass of food waste is cleaned of foreign elements, such as glass, metal, and plastic.
2. Further, the food waste is crushed at special installations.
3. Crushed food waste goes through a homogenisation process to improve fermentation processes.
4. After all the stages of preparation, the fermentation process begins, which may vary in temperature and dry matter content. For example, if the temperature is higher, then fermentation will go faster.

The whole process takes place in special equipment and under the supervision of specialists, the final product of this method is biogas. Biogas obtained by the method of anaerobic decomposition of food waste contains about 60-70% methane and has an energy potential several times greater than that of hydrogen fuel. In addition, the remains of the fermented mass can be used as a fertiliser for the agro-industrial complex. V. Ducasse et al.[10] define vermicomposting as the process of processing consumer waste using soil biota, that is, the use of special worms to accelerate the processing. Vermicomposting is considered to be a biotechnological method4). A.H. Sheugen[11] states that the first production vermicultures appeared in the 1940s in the USA. Now the cultivation and breeding of vermicultures are widespread in Western Europe, Southeast Asia, the USA, and Japan. Currently, 12 to 15 species of earthworms are used as vermiculture, depending on the climate and natural conditions of the country, as mentioned in the studies of such authors as K. Singh et al.[5], A. Khandagle et al.[12]. *Eisenia fetida* is the most versatile species, adapts to different types of organic waste, and is characterised by rapid growth and fertility. For vermicomposting with this type of earthworms, the following conditions must be observed:

– temperature – 20-28°C;
– humidity – 70-80%;
– the pH value of the medium – from 0.5 to 8;

– regular addition of organic materials;
– oxygen saturation.

Compliance with these conditions contributes to the active growth and reproduction of earthworms, thereby leading to accelerated processing of food waste. The processing of food waste by vermiculture is considered a waste-free technology, as a result of which it is possible to obtain biohumus[13]. Earthworms destroy spores of pathogenic fungi and bacteria during their digestive process. Biohumus obtained by vermicomposting is an environmentally friendly product that contains no pathogenic microorganisms and is enriched with a high carbon, potassium, phosphorus, and calcium content. Biohumus is used as the main organic fertiliser in the agro-industrial complex, preparation of soils for backfilling in housing, industrial, and road construction, and for soil reclamation. The process of processing organic waste using vermicultures is a more natural and environmentally friendly process with the production of valuable components to solve the food supply of the population: obtaining biofertiliser and animal feed.

While anaerobic decomposition yields biogas with a high energy potential, vermicomposting offers the advantage of producing biohumus, an environmentally friendly organic fertiliser enriched with essential nutrients. Additionally, vermicomposting is considered a waste-free and more natural process, contributing to the food supply through the production of biofertiliser and animal feed. The choice between the two methods depends on specific objectives and preferences, with anaerobic decomposition being suitable for energy production and vermicomposting being an eco-friendly solution for sustainable agricultural practices.

3. Materials and Methods

Vermitechnology was chosen as the focus of the study because it is considered a natural and environmentally friendly method of recycling organic waste. This technology involves using earthworms to decompose organic matter, which results in the production of valuable components like biohumus, a nutrient-rich organic fertilizer.

In the course of the study, theoretical and empirical research methods were used, in particular, experiment. The experiment was conducted based on theoretical knowledge that determines the formulation of research objectives and the interpretation of its results. The study is focused on identifying the integrity of the object of study, a comprehensive search for solutions. The study utilized various theoretical methods, including synthesis, analysis, comparative-descriptive, and ascent from the abstract to the concrete. These methods helped the researchers gain a comprehensive understanding of vermitechnology, analyze its benefits and challenges, compare it with other waste management approaches, and translate theoretical knowledge into practical recommendations for its implementation in Kazakhstan's waste management and agriculture. The features of the system of processing consumer waste in modern conditions and the level of use of mineral and organic fertilisers in the agricultural sector of Kazakhstan are examined.

Based on the theoretical basis, an effective empirical method is implemented – an experiment. The phenomenon under study was observed under specially created and controlled conditions, which allows for expecting the reproducibility of the process when similar conditions are repeated. The objects of the experiment were red California worms, soil, cattle manure, chicken manure, and food waste. The selected soil was divided in equal volumes into six boxes, and the materials selected for processing were separated and mixed with the soil. That is, two boxes of soil mixed with cattle manure (Cattle-1 and Cattle-2) were formed, two boxes of soil mixed with chicken manure (CM-1 and CM-2), two boxes of soil mixed with food waste (FW-1 and FW-2). Each box was populated with 10 red California worms (Figure 1).

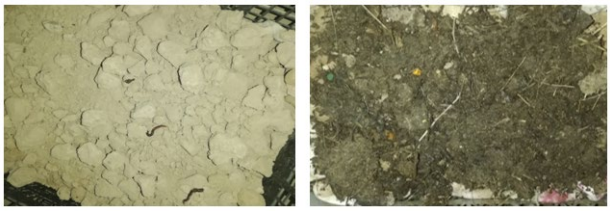

Fig. 1: Soil sample before and after mixing with cattle manure.

The experiment was conducted for 2 months at a temperature of 25-30°C. Considering the predisposition of worms to moisture, the samples were watered frequently. The samples were stored in the shade with a temperature of 25-30°C since this type of worm does not tolerate direct sunlight and temperature drops. In addition, the samples are aimed at determining the metal content and bacteriological analysis[14]. The process was controlled by the following indicators[15]:

– the total number;
– the number of mature specimens;
– the number of immature specimens;
– total and individual productivity (the number of cocoons per vessel and per mature worm);
– the yield of juvenile specimens from cocoons;
– the ratio of age states and vertical distribution in the substrate.

After the experiment, theoretical generalization was used to identify typical features and patterns, optimizing the process and finding economically and environmentally beneficial solutions for the examined problems.

4. Results

According to the statistics of the FAO, more than 1 billion tonnes of food products – one-third of the total

world food production is lost annually. In addition, according to the studies of FAO in Kazakhstan, food spoilage can be observed at many stages of harvesting, transportation, storage, and consumption, all of which lead to an increase in the volume of food waste[16]. The secondary use of municipal and agricultural waste for the conservation of biodiversity, resource conservation, and the production of biofertilisers and bio-feeds remains an urgent task all over the world. Waste management processes are a developing industry in the country. The rates of waste processing in Kazakhstan are shown in Figure 2.

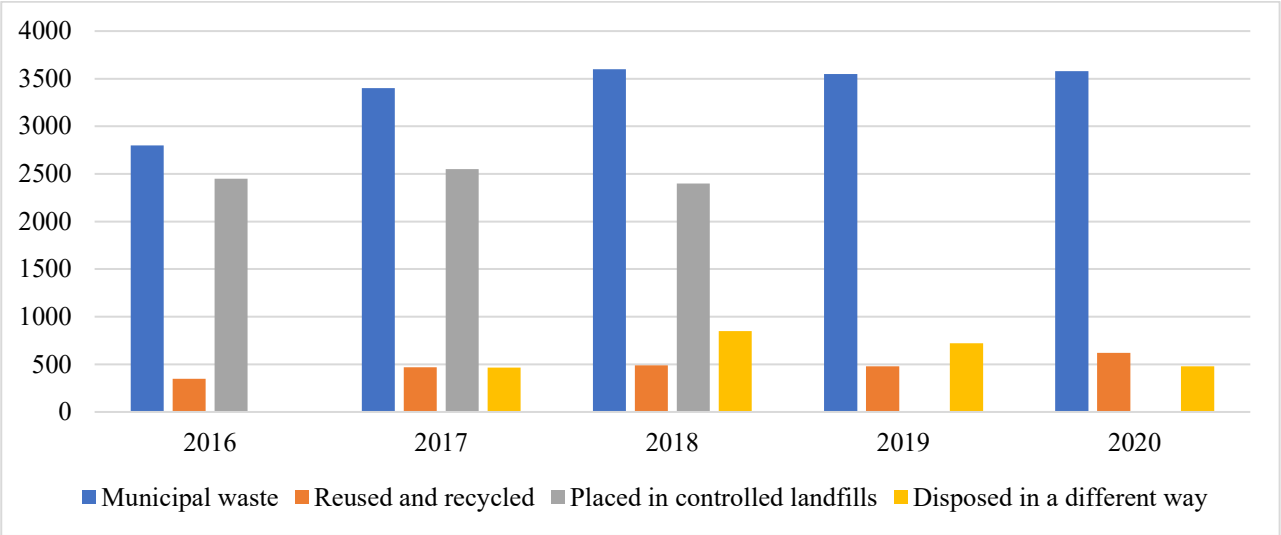

Fig. 2: Processing and disposal of municipal waste in the Republic of Kazakhstan, thousand tonnes.
Source: Environmental protection in the Republic of Kazakhstan: Statistical compendium[17].

Current data on the use of various types of fertilisers in the agricultural sector of the Republic of Kazakhstan are shown in Figure 3.

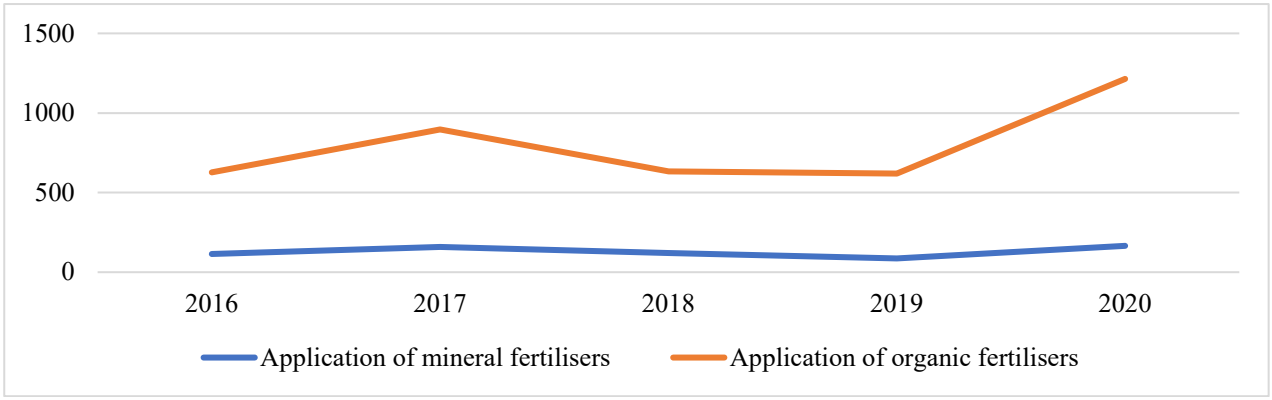

Fig. 3: Introduction of mineral and organic fertilisers into the soil of the Republic of Kazakhstan, thousand tonnes.
Source: Environmental protection in the Republic of Kazakhstan: Statistical compendium[17].

Figure 4 shows data on the number of pesticides applied per unit area of agricultural land.

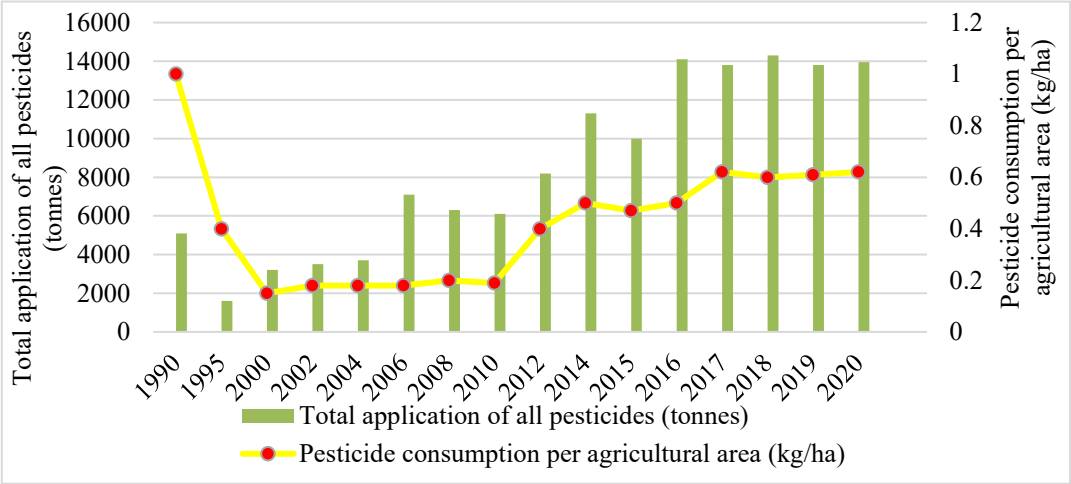

Fig. 4: Introduction of pesticides on the territory of Kazakhstan.
Source: Environmental protection in the Republic of Kazakhstan: Statistical compendium[17].

Figure 5 shows the main sources of food waste generation.

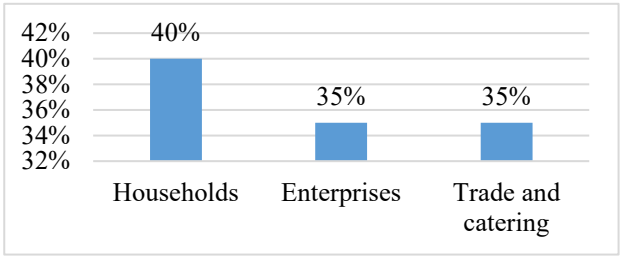

Fig. 5: Comparative indicator of food waste generation in different areas.

When evaluating methods for processing food waste, it is essential to consider their specific characteristics, such as the challenge of transferring waste to farms due to the heterogeneity of organic waste, which can complicate separate collection. Additionally, organic waste is unsuitable for waste incineration plants because of its high moisture content.

In this regard, the use of vermiculture is one of the most effective ways of processing food waste. Waste recycling using vermicultures is a more natural and environmentally friendly process that has great potential for widespread distribution since the recycling process is available and can be used in private households. Another advantage of vermicultures is the acceleration of the decomposition of organic substances with the possibility of processing them into humus-containing fertilisers. Vermicultures are characterised by a rapid growth rate, fertility, and a fairly long life expectancy[11]. Due to these qualities, a large volume of biomass can be obtained in the process of waste processing, which can be used as a protein supplement for animal feed. The composition of vermicompost obtained during the processing of consumer waste is characterised by a variety of physicochemical properties. A number of similar parameters of vermicompost are given below in Table 1.

Table 1. Physico-chemical properties of vermicompost.

Trait	Oscillation
pH	6-8
Humidity, %	40-60
Ash content, %	15-80
C/N	8-25
C_{org}, %	10-40
$N_{general}$, %	0.2-3
$R_{general}$, %	0.3-3
K_{total}, %	0.6-2.8

During the preparation of this section, the analysis of samples obtained during the experimental work was conducted. The analysis was conducted to determine the key properties and content of chemical elements. In addition to humidity, temperature, and nutrient medium, the pH level is also important for the continuation of the vital activity and development of California worms. The level of pH indicators in the examined samples is shown in Figure 6 (The studies were conducted according to the GOST 7636-85[18] methodology).

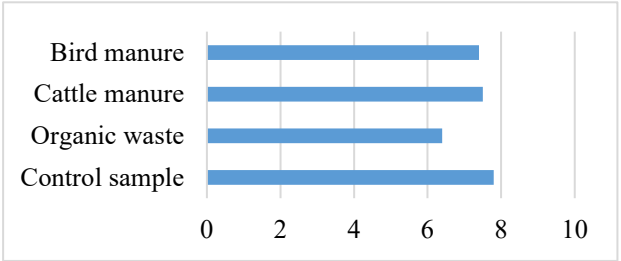

Fig. 6: pH values in the examined samples.

According to the data in Figure 6, a neutral environment of organic food waste can be observed, whereas cattle and

poultry have a more alkaline environment compared to the control sample. Figure 7 shows the volumes of dry matter content in the samples under study.

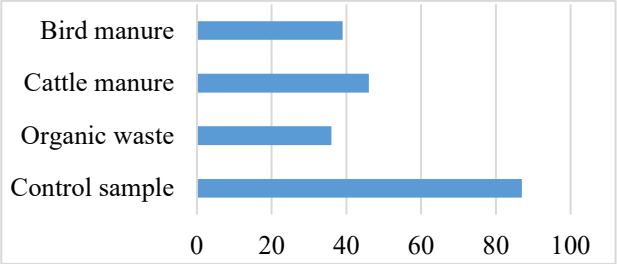

Fig. 7: The content of dry substances in the examined samples, %.

The dry element consists of an organic part and an inorganic part. The element of the mixture includes the basic: fats, carbohydrates, and proteins structural materials – lignin, cellulose, hemicellulose, and fibre. A high content of dry substances is observed in bird manure, perhaps this is due to the low moisture content and the presence of a diverse composition of various elements. Comparing the data in Figure 7 with the data in Table 1, it can be concluded that the most optimal pH indicator for worms is in organic waste, and samples with cattle and bird manure can bring uncomfortable manifestations for the development and reproduction of worms. Based on the results of a literary review of various methods of vermicomposting, it was identified that the processing and reproductive capabilities are strongly influenced by temperature and humidity. Comparing the samples under study, in the variant with organic waste, a higher moisture content is observed, and other samples are characterised by a dry structure, with an approximate moisture content of 40%. In general, all samples are acceptable for life. The products obtained as a result of the waste processing by the consumption method are characterised by a rich content of chemicals. Of particular interest is the investigation of the possibility of changing the content of nitrogen isotopes and humic acids, and in vermicompost – under the influence of the vital activity of worms. The percentage of nitrogen and humic acids in the samples is given in Table 2.

Table 2. The content of nitrogen and humic acids in the samples, %.

No.	Nitrogen	Humic acids
Organic waste	0.61	2.56
Cattle	0.87	6.62
Bird manure	1.05	7.04
Humic acids	0.32	15.83

According to Table 2, it can be stated that worms activate microbiological processes and increase the production of nitrogen and humic acids. For example, samples with bird manure have a high content of nitrogen and humic acids, and organic waste has the lowest content of these substances. Thus, it is concluded that the activity of worms in waste processing contributes to nitrogen fixation, thereby contributing to plant growth. Table 3 shows the content of chemicals in the samples under study. Based on the data, it can be stated that the waste processing products by worms can be used as a nutrient medium that allows adding all the necessary macro- and microelements to the soil and improving the physical and mechanical properties of the soil.

Table 3. Chemical content in samples, %.

No.	Phosphorus	Potassium	Magnesium	Zinc	Iron	Copper	Calcium	Nitrogen
Control sample	0.08	0.47	0.23	1.04	1.24	0.38	0.94	0.32
Organic waste	0.091	1.79	1.218	3.218	2.48	0.022	6.24	0.32
Cattle	0.223	2.13	1.97	11.252	4.17	0.105	4.34	0.61
Bird manure	0.178	2.81	2.05	9.313	5.62	0.093	6.83	1.02
								0.87

Table 4 shows the analysis of changes in the content of chemicals in the samples.

Table 4. Analysis of changes in the content of chemicals in samples.

No.	Nitrogen	Phosphorus	Potassium	Magnesium	Zinc	Iron	Copper	Calcium
Control sample	0.32	0.08	0.47	0.23	1.04	1.24	0.38	0.94
Organic waste	0.61	0.091	1.79	1.218	3.218	2.48	0.022	6.24
ΔY1	0.29	0.011	1.32	0.988	2.178	1.24	-0.358	5.3
i	1.906	1.138	3.809	5.296	3.094	2	0.058	6.638
T, %	90.6	13.8	280.9	429.6	209.4	100	-94.2	563.8
The nature of the change	Increase	Increase	Increase	Increase	Increase	Increase	Decrease	Increase
Cattle	1.02	0.223	2.13	1.97	11.252	4.17	0.105	4.34
ΔY2	0.7	0.143	1.66	1.74	10.212	2.93	-0.275	3.4
i	3.188	2.788	4.532	8.565	10.819	3.363	0.276	4.617
T, %	218.8	178.8	353.2	756.5	981.9	236.3	-72.4	361.7
The nature of the change	Increase	Increase	Increase	Increase	Increase	Increase	Decrease	Increase
Bird manure	0.87	0.178	2.81	2.05	9.313	5.62	0.093	6.83
ΔY3	0.55	0.098	2.34	1.82	8.273	4.38	-0.287	5.89
i	2.719	2.225	5.979	8.913	8.955	4.532	0.245	7.266
T, %	171.9	122.5	497.9	791.3	795.5	353.2	-75.5	626.6
The nature of the change	Increase	Increase	Increase	Increase	Increase	Increase	Decrease	Increase

Using linear coefficients of change (differences) in the ranks of the shares (Spearman correlation), data on structural changes were obtained before and after organic waste treatment, where substantial changes in cattle manure are visible. Changes in the composition of mineral substances are shown, namely, the maximum values were manifested in cattle: nitrogen, phosphorus, and zinc, and in bird manure: potassium, calcium, magnesium, and iron, on the contrary, a decrease in the composition during vermicomposting show all the compositions of organic substances.

5. Discussion

Environmental pollution due to improper handling of solid waste is a global problem. Open disposal of consumer waste is currently the main implemented system of waste treatment and final disposal in developing countries, one of which is Kazakhstan. Irrational disposal of solid waste is the cause of serious and diverse social and environmental consequences that negatively affect the pursuit of sustainable development. Many researchers investigate the problems of recycling consumer waste using innovative progressive methods based on basic natural processes. The scientific community in many countries of the world today is in search of technologies that can simultaneously solve the problem of environmental tolerance, economic viability, and social popularity. In such conditions, various areas of biotechnology are becoming increasingly important, including combinations of the maximum possible biological, biophysical, and biochemical factors affecting waste of various origins[19)-22)].

Researchers K. Samal[9)] and K. Anand[6)] are convinced that vermitechnological processes consisting of vermicultivation and vermicomposting are a progressive highly effective method that allows not only the optimising processing of consumer waste but also the creation of an organic unique fertiliser – biohumus during the process. During the dominance of the trend of environmental friendliness and organicity in all production processes, the possibility of additional environmental and economic benefits should be considered a priority[23),24)].

A positive consequence of vermitechnology is the production of a substantial amount of feed protein in the form of worm biomass, which is necessary for animal husbandry and in the production of compound feeds. N. Karmegam et al.[8)] and Z.W. Song et al.[25)] focus on this advantage of the examined system of organic waste

disposal in their papers. They convince of the multifactorial nature of the positive consequences of the introduction of complex technologies for the processing of consumer waste, covering the spectrum of their activities processes with a positive economic effect. The moment of economic expediency is especially important for countries with developing economies, to which Kazakhstan belongs[26]. Modern researchers M.S. Ayilara et al.[27], N. Ferronato and V. Torretta[28] insist on this in their papers. They are rightfully convinced that the ecological and economic efficiency of the waste management technologies used, in particular, organic ones, serves as a catalyst for the social popularisation of environmentally efficient technologies, and is also of interest for investment. The economic efficiency of the examined biotechnology is determined not only by the properties of the vermicompost itself but also by several other advantages[3),29),30)]. Among them, it is necessary to highlight the following:

– increasing the yield of fields while reducing the cost of expensive harmful fertilisers and pesticides;

– production of environmentally friendly organic agricultural products;

– improving the quality and preservation of products;

– increasing the level of digestibility of feed by adding full-fledged feed additives obtained using worm biomass;

– improvement of the soil and environment around livestock complexes;

– the possibility of creating waste-free, environmentally friendly, and highly profitable agricultural production.

Another aspect of the positive effects of the use of vermitechnology is notable. Ultimately, its competent application contributes to solving environmental problems arising from the accumulation of large amounts of manure on livestock farms[6),31)]. The introduction of vermiculture allows for reducing the volume of manure, and the cost of its processing, eliminating the smell, and improving the physical properties of manure, turning it into a qualitatively new type of organic fertiliser in a short time[32),33)].

W. Fadhullah et al.[34], S. Sarkodie and P. Owusu[35] consider the prospects of organic technologies for the waste-free processing of consumer products and the accompanying popularisation of environmentally efficient processes in the production of products directly related to agriculture in scientific publications of recent years

The successful application of vermicomposting and vermiculture in waste management and agriculture was described by B.P. Naveen[36]. In Bangalore, India, the municipal authorities implemented a large-scale vermicomposting project for the utilisation of municipal organic waste. Earthworms, particularly Eisenia fetida, were used in community vermicomposting units to process food waste from households and markets.

J. Pico-Mendoza et al. explored the potential of vermiculture in managing coffee processing residues in Costa Rica[37]. The *Perionyx excavatus* earthworm species were utilized to vermicompost coffee cherry waste. The resulting vermicompost was rich in nutrients, improved soil fertility, and increased crop productivity in coffee plantations. On the other hand, Sam Smout did his great research at the University of Cape Town[38]. The University of Cape Town implemented a vermicomposting initiative to utilise organic waste generated on campus. Large-scale vermicomposting systems were installed in the university's canteens and dining halls. Food waste was collected and processed by *Eisenia fetida* worms, resulting in nutrient-rich vermicompost. The vermicompost was utilised in campus gardens and green spaces, promoting waste management and supporting the university's commitment to environmental conservation.

Thus, it can be stated that the use of complex technology of vermicomposting and vermicultivation allows effectively combining optimal processing of organic waste, cost-effective soil biohumification, and ecological regeneration of local agroecosystems. This combination, against the background of the general desire of developing countries to implement the principles of sustainable development and development of organic production, opens up substantial opportunities and prospects for the relevant industries in Kazakhstan, including foreign investment programmes. The subject of the study requires attention from the scientific and practical side, further research of the possibilities of implementing complex vermitechnologies, their ecological and economic efficiency and importance.

6. Conclusions

According to the results of the study, there is an increase in the number of worms, and priority preferences in the processing of organic waste. In general, during the experiment, the timing of the processing of various types of waste, the specific features of the life and habits of worms, the adaptation of worms to new types of food additives and general monitoring of the processing process were determined. As a result of the processing of organic waste by compost worms, a secondary product is obtained – biohumus, which is necessary due to the problem of soil dehumidification as a fertility restorer, and as a soil solution, which is an economically profitable fertiliser-top dressing for ornamental plants. The experimental work will continue using more problematic types of soil and using other types of organic waste, such as poultry manure, and cattle to examine the impact of California worms on the processing of organic waste in more detail.

Based on the above, it can be assumed that chicken manure, due to its chemical composition, is most suitable for worms. In addition, these nutrients are in more easily accessible compounds. The results of the analysis of the soil sample using chicken manure showed that chicken

manure is the most comfortable environment for the life of worms since a good increase in young specimens is noticeable in one of the samples. Compared to the cattle samples, the samples containing chicken manure were well processed, and the humus content in the soil is observed. In a sample with chicken manure, 30 young specimens, 4 large, and 5 small specimens were identified. By its chemical composition, chicken manure has high fertilising qualities and surpasses cattle and organic waste, and in terms of speed of action, it is not inferior to mineral fertilisers. Thus, solving the problems of processing organic waste, several environmental issues are being solved: waste recycling, obtaining vermicompost, animal feed, biofertilisers, providing food to the population, reducing greenhouse gases, land degradation, and pollution of water systems.

In conclusion, all the objectives of the research have been successfully completed, demonstrating the effectiveness of vermitechnology in waste recycling and its potential for agricultural optimization. This study opens up several prospects for further exploration, including long-term impact assessment on soil health and crop yield, comparative studies with other waste recycling methods, economic analysis for large-scale implementation, and optimization of worm species. Additionally, there are prospects for scaling up applications, evaluation of environmental impact, nutrient cycling studies, and technological advancements to enhance the vermicomposting process.

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