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Biorecycling of Organic Waste as a Universal Ecoclimatic Project and Increasing the Resource Capacity of Cultural and Natural Ecosystems

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Abstract

The problem of organic waste generation has long grown into a global environmental problem. There are different methods for recycling organic waste of various origins and morphological states. But the vast majority of the organic component of the total mass of waste generated in the world is not processed effectively. In 2022 together with industrial partners, the research and production site (RPS) was created for the development and testing of technologies for recycling organic waste using insects, and (hereinafter referred to as the RPS). During this period technical specifications were developed and registered for the production of two products of biorecycling of organic waste by Hermetia illucens larvae (feed for unproductive animals – dogs, cats, chickens, geese, ducks, pigs) and vermicompost enriched with beneficial microflora. The scientific group of the RPS, in collaboration with representatives of universities and research centers from different regions of Russia, with the support of the Sibur company, developed the ecoclimate project to create five enterprises in the Western Cis-Urals for the biorecycling of organic waste. Using five organic waste landfills as an example, it is shown that the environmental and economic efficiency will be 180 thousand tons of CO2-eq./year of carbon units. The level of biorecycling of organic agricultural and other waste is 120 thousand tons/year and more. Thus, it is possible to eliminate the deficit in the market for secondary raw materials, vermicompost and feed additives. This is aimed at achieving ecologically and climate-optimized organic farming. The results and material of our work can be used in handling organic waste from crop and livestock production, from the agro-feed and food industries, from public utilities. The work can be a scientific and methodological basis for biorecycling of organic waste from urban economic facilities and other areas of public production. This is the example of modern environmental culture and ecologized self-awareness of nature users.

Keywords: *Organic Waste, Waste Recycling, Biorecycling of Waste, Secondary Raw Materials, Protein Feeding, Organic Fertilizers, Biotechnology, Rationalization of Agriculture, Ecoclimatic Project, Reduction of Greenhouse Gas Emissions, Carbon Sequestration and Deposition, Carbon Units.*

Introduction

The problem of organic waste generation has acquired global proportions. Large cities and certain types of agricultural production regularly generate millions of tons of organic waste, both plant and animal origin. According to the study commissioned by the Food and Agriculture Organization of the United Nations (FAO), more than 1 billion tons of food waste are generated annually (Surendra et al., 2020). According to the latest data, of the total volume of waste generated, almost 998 million tons is agricultural waste (Marak et al., 2024).

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Given the growth of the planet's population, the need for intensification of agricultural production will increase. Consequently, the volumes of organic waste generated from agriculture, agro-food, agro-feed, food and communal production will increase.

The limitations of ecologically sustainable interactions between crop and livestock systems are obvious due to insufficient or minimal involvement of generated waste in further agricultural production. This is

especially obvious in terms of increasing bio productivity and soil health, increasing ecological stability and improving the resource capacity of agricultural lands and various agroecosystems.

According to the Food Waste Index report, prepared by the United Nations Environment Program (UNEP) with the participation of the international charity Waste and Resources Action Program (WRAP) humanity wasted about 19% of the food produced in 2022 (1.05 billion tons). This was reported by the Associated Press (Mureithi, 2024).

Handling organic waste due to its critical increase in volumes, including from the agricultural sector, is a problem for many regions of the world. This problem is also relevant for the countries of the East European Plain with the high emphasis on agricultural production. This problem is also characteristic of Russia. According to information from the Public Law Company "Russian Ecological Operator", announced on May 1, 2020 during the presentation of the federal waste management scheme, in the Russian Federation there are more than 1,200 waste disposal enterprises with the total processing capacity of more than 37 million tons of waste annually. At the same time the current recycling rate, in particular for municipal solid waste (MSW), varies between 4−5%, i.e. no more than 3.5 million tons/year. Thus, with the volume of MSW accumulation up to 65 million tons/year, only less than 10% of the available capacities are occupied with waste disposal.

In many regions of the East European Plain, agricultural nature management and agricultural production occupy leading positions in social production. In the center and east of the East European Plain, the agricultural sector of industry is widely developed, and there are also a number of large livestock complexes. In the cities and regional centers of the republic, a large amount of waste is generated by hypermarkets and public catering organizations. This is due to the existing natural landscape, cultural, historical and socio-economic conditions. In many ways, the moderate climate and the diversity of soil and vegetation contributed to the widespread use of agriculture and related livestock farming. However, the level of rationalization of land use and bioresource management remains low. The level of utilization and processing of organic waste remains extremely insufficient. This can be seen in different regions of the East European Plain, including its western, central and eastern regions.

For example, in the Western Cis-Urals, problems of waste generation and waste management have become more acute in recent years. The Udmurt Republic occupies an area of 42.1 thousand square kilometers with the population of 1442 thousand people. Every year, on average, about 4 million cubic meters of waste are generated, and only 3-4% of this amount goes into industrial processing, the rest is sent to landfills and becomes a source of environmental pollution. The agricultural sector of the economy is actively developing in Udmurtia: there is a great number of large crop and livestock complexes, a wide range of enterprises producing food plant, dairy, meat and related products. In this regard, the volumes of generated organic waste are object of increased interest when considering the problem of waste in the republic. The share of agricultural waste of hazard classes III–V (of the total volume of generated production and consumption waste) is 41.8% (546 thousand tons). In the Western Cis-Urals (including the Udmurt Republic), as well as in a number of other regions of the East European Plain, the ecological and economic synergy from the minimal interaction of crop production, livestock farming and subsequent use of organic waste remains low. As a result, there is an obvious gap in maintaining and increasing the resource capacity of lands and agroecosystems.

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The average annual volume of production and consumption waste in the republic is about 700 thousand tons or 2.8 million cubic meters. At the same time, 70% of the generated waste comes from solid household waste, 30% from the activities of enterprises and organizations (industrial waste).

Agricultural complexes are the leading suppliers of organic waste in the world. This environmental problem continues to worsen: in Asia (Wani et al., 2017; Xiang et al., 2022; Zhang, 2022; Gholipour et al., 2024; Manzoor et al., 2024; Marak et al., 2024; Wang, Cui, 2024), in the Central and South America (Van der Velden et al., 2021; Vivallos Soto et al., 2022), in Africa (Karani et al., 2021; Nath et al., 2023; Dagoudo et al., 2024), in Europe (Radović et al., 2023; Kofroňová et al., 2024; Toplicean, Datcu, 2024),

in Russia (Arkhipchenko et al., 2020; Shaikhiev et al., 2020; Agapkin, Makhotina, 2021) and adjacent territories (Kundius, Bayarsukh, 2023), as well as in other regions of the world. That is, this is a global ecological and production-economic problem. The issue of utilization and processing of organic waste, including agricultural waste, has acquired a universal practical necessity.

Global weather and climate change also make the problem of organic waste generation and the difficulty of handling it more pressing. Disposal of organic waste is closely related to the problem of climate warming. Despite measures taken under the UN Framework Convention on Climate Change to limit greenhouse gas emissions, their concentration continues to increase. The concentration of carbon dioxide in the Earth's atmosphere is steadily increasing. In 2021 it reached another high. The average annual value at stations of the Russian Federation located under background conditions approached the value of 419 million-1.

In social production, it is necessary to designate the transition to climate neutrality in land use (Xiang et al., 2022; Pogibaev, Larionov, 2024; Sharma et al., 2024), in the recycling of agricultural products, in improving the resource qualities of soils and agroecosystems (Xiang et al., 2022; Galstyan et al., 2023; Larionov al., 2024). This is largely due to the need for greening the handling of agricultural waste. In this aspect, ecological and climatic management of organic waste appears to be a promising scientific and industrial direction. Decarbonization in crop and livestock production is both ecologically and economically feasible. Emissions and absorption of greenhouse gases by sectors of the Intergovernmental Panel on Climate Change (hereinafter referred to as IPCC) are presented in Table 1. The main drivers of changes in emissions in the Russian Federation are the general trends in the development of the national economy, the integral indicator of which is the dynamics of the GDP, changes in the overall efficiency of the economy and, mainly its energy efficiency, changes in the structure of the GDP and the structure of the fuel balance. The certain contribution to changes in emissions is made by a general trend and interannual fluctuations in air temperature on the territory of the Russian Federation, which exert their influence indirectly through changes in the use of fossil fuels.

Table 1. Greenhouse Gas Emissions by Sectors of the Intergovernmental Panel on Climate Change

Sectors	Emissions, million tons CO_2-ecv.				
	2018	2019	2020	2021	2022
Energy	1686.3	1679.4	1591.0	1676.0	1632.0
Industrial processes and product use	244.7	239.1	246.0	254.4	244.5
Agriculture	112.9	114.6	116.8	119.2	119.8
Land use and forestry (LU&F)*	-664.8	-634.1	-653.3	-594.6	-617.6
Waste	87.4	89.1	91.5	94.0	96.2
Total, excluding LU&F	2131.3	2122.2	2045.3	2143.6	2092.5
Total, including LU&F	1466.5	1488.0	1392.0	1549.0	1474.8

Values are rounded

** The minus sign corresponds to the absorption of greenhouse gases from the atmosphere

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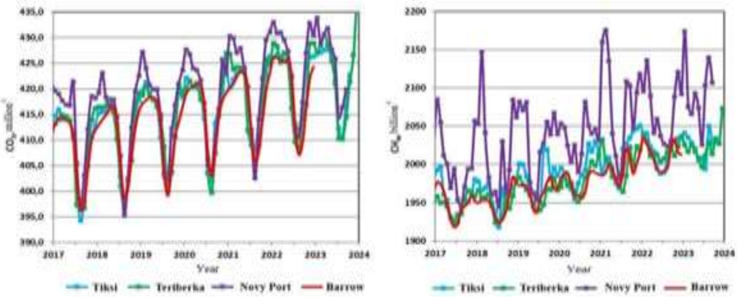
Over the past three years, both at the Russian Arctic stations and on a global scale, an acceleration in the growth of methane concentrations has been observed. Methane enters the atmosphere from both anthropogenic and natural sources, while an increase in natural emissions can be caused by climate warming. Which of these reasons is responsible for the change in the growth rate of methane concentration has not yet been established. Scientific research aimed at elucidating the possible reasons for the increase in the interannual growth of methane concentrations is presented in the WMO GHG Bulletin No. 18 dated October 26, 2022. The joint consideration of changes in the concentration and isotopic composition of methane over time indicates a significant role of biogenic sources in this process (Review of the state and pollution…, 2024).

The results of greenhouse gas monitoring at the Russian Arctic stations are presented in Figure 1 (monthly average concentrations of CO2 and CH4 compared with data from Barrow station).



(a) **(b)**

Figure 1. (A) Time Course Of CO2 Concentrations at The Russian Arctic Stations in Comparison with Data from Barrow Station; (B) Time Course Of CH4 Concentrations at The Russian Arctic Stations in Comparison with Data from Barrow Station

A significant portion of solid waste consists of organic materials. Organic substances contained in waste contribute to increased greenhouse gas emissions and the leaching of organic substances into water bodies causing their eutrophication. In this regard, a promising direction may be the development of technologies that allow transforming organic waste into raw materials that can be in demand: fertilizers, compost or sources of feed proteins and fats. If such technologies are implemented with the help of living organisms – bacteria, protozoa, worms, insects – they are methods of biological recycling (Bastrakov, 2023). It should be noted that it is possible to improve the resource capacity of soils, agrophytocenoses and agroecosystems in general through the use of fertilizers and biohumus from organic waste from crop and livestock production through biological recycling. The synergy and advantage of beneficial ecological and economic effects lie in the possibility of using biorecycling plant and livestock waste in the future in plant growing, livestock farming, agro-feed and agro-food production, etc.

The world is witnessing a gradual transition of countries to a circular economy with a developed system of recycling products, for example, processing organic crop and livestock waste to produce protein for feeding animals and poultry. It is the so-called trend of switching to high-protein feed with low cost for farm animals (Khatuntsev et al., 2016). Processing organic agricultural waste with the help of fly larvae solves several critical challenges of agricultural development: production of cheap and high-quality animal protein; involvement of biological waste in secondary processing; reducing the burden on the environment (Dedyaeva et al., 2018), improving the condition and resource capacity of lands for crop and livestock natural resource management. This type of feeding is also necessary for use in the production of pet food.

Mass production of insects is also promising from an environmental point of view due to the low greenhouse gas emissions, small area required to produce 1 kg of protein, reduced space use due to decreasing competition between feed and food, and the ability to convert organic side streams into valuable protein products. In particular, the use of insects in waste bioconversion represents a new approach and an excellent example of the sustainable circular economy (Oonincx, de Boer, 2012; Makkar, 2018; Meneguz et al., 2018; Alagappan et al., 2022).

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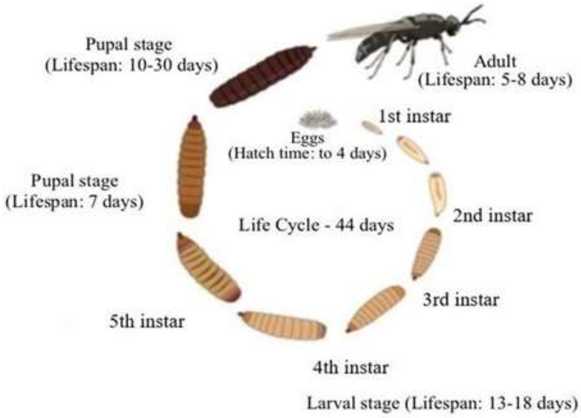

Figure 2. Life Cycle of Hermetia Illucens (Surendra Et Al., 2020).

As a promising and more environmentally friendly method of recycling organic waste, we can consider processing using environmental biotechnologies – the use of living organisms as an object for recycling. One such object is the Black Soldier Fly (Hermetia illucens). The larvae of this fly are used for the production of cosmetic products, biological additives for feed, and also in pharmaceuticals. Currently, research is being conducted to study the potential of using this type in the field of organic waste processing. Our research is aimed at studying the possibility of using the larvae of the Black Soldier Fly (H. illucens) for recycling organic waste. Beneficial ecological and economic effects are associated with the development characteristics of this species (Figure 2).

The H. illucens larvae are grown on the substrate made from plant raw materials or food waste, and its bioconversion reaches 77%, which determines the low cost of the finished product (Ushakova et al., 2018). The advantage of larvae as the component of feed is their high protein content – 35–48%, while the share of digested protein accounts for 85–95% (Nekrasov et al., 2019). The fat content in the larvae is also high and amounts to 20–45% (Ushakova et al., 2016). It is important that there is no shortage of the necessary volumes of plant materials for the biological recycling of organic waste (waste from crop farms, waste from the production and consumption of plant foods, waste from plant feed for animals, plant litter, etc.). There is also no shortage of quality raw materials for biorefining from livestock waste and from mixed waste of plant and animal origin.

Larvae as universal decomposers can grow and develop on various substrates obtained from waste from the crop and livestock production, agro-food industry, or mixed urban organic waste (Diener et al., 2011), food waste from restaurants and markets, fruit and vegetable waste, beer, food industry waste, animal manure, for example, bird droppings, cow and pig manure, human feces and fecal sludge, slaughterhouse waste, fish waste (Asylbekova et al., 2022). The use of such animal substrates and animal manure is prohibited in the European Union in mass larval rearing for feed production, but these data make insect-mediated bioconversion a promising waste treatment technology. Numerous studies have shown that H. illucens larvae are able to utilize more than half of the organic material on which they develop converting it into valuable organic fertilizer. These larvae can develop on biorecycled substrates from plant waste and plant litter in vegetable gardens and horticultural areas, litter from green spaces in urban, suburban and rural areas, as well as on biorecycled substrates from mixed organic waste.

The need for organic and regenerative farming is now evident throughout the world. Promising organic fertilizers are needed to improve the efficiency of plant growing, soil bioreclamation, and to increase the sustainability and ecological functionality of greenery plantings, nursery and garden and park phytocenoses. Promising organic fertilizers are needed to solve problems of combating the destruction and degradation of agricultural lands.

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The process of recycling waste using fly larvae differs from other disposal methods. Organic residues

particles during the process of feeding and digestion. After extracting nutrients from organic waste, the volume of the latter is reduced by 70–80%. The maximum bioconversion rate is at least 0.9 kg per day per square meter, while the specific productivity should be at least 25 mg of substrate per larva per day at the stocking density of 5 individuals per square centimeter (Bastrakov et al., 2015).

The area of landfills in the Russian Federation is approximately 15 thousand hectares. The recycling of organic waste by the larvae of the H. illucens fly – as a new promising direction in the development of biotechnology is an opportunity to partially reduce the load on landfills. In addition, this disposal method can be a source of income in the form of profit from the sale of products obtained as a result of the bioconversion of organic raw materials by larvae, as well as from the sale of living biomass of larvae as raw material for the production of feed and cosmetic products.

Meticulous Research estimates that the global market for the H. illucens will reach 2.57 trillion USD by 2030. The issues of breeding of the H. illucens to obtain feed protein are already being actively pursued in the USA, Canada, Holland, Austria, Greece, Germany, the South Africa, India, China and other countries. According to the IPIFF experts (T19 he International Platform of Insects for Food… 2024), by 2030 the global insect protein market in value terms will reach 8 billion USD. High protein raw materials account for 50 to 70% of livestock production costs. In 2017 the global feed industry was valued at $430 billion.

Another product of waste conversion by larvae is vermicompost, which is a valuable organic fertilizer. The annual consumption of organic fertilizers in Russia is about 70.0 million tons (for comparison, mineral fertilizers are 2.7 million tons). The market potential is high, since humus provides more nutrients per unit mass than traditional types of organic fertilizers. By order of the Government of the Russian Federation No. 2761-r dated October 10, 2023 the H. illucens is included in the list of agricultural products. For example, in Canada, the USA, and the European Union, the H. illucens flies have the status of an approved biomaterial for use as feed for farm animals (Hetényi, 2022). In these and other countries, issues are being worked on assessing the potential for bioconversion of agricultural, agro-food and mixed organic waste. However, a number of open questions remain regarding the assessment of the possibilities and prospects of using H. illucens in the biorefining of agricultural organic waste. It is especially important to have an idea of the efficiency of the H. illucens in recycling organic waste to solve agricultural, economic and ecoclimatic problems.

Thus, our research direction seems relevant for solving ecological-climatic, agronomic, agro-feed and other agricultural and production problems of our time. Biorecycling of organic waste, among many positive functional qualities, is declared for the rationalization, greening and isolation of agriculture and related branches of agriculture, agro-industrial and recycling industries. The declared global trend towards organic agriculture and climate neutrality also implies meeting the growing demand for environmentally and hygienically safe biomaterials, and for affordable and high-quality biosubstrates.

Materials and Methods

In 2022, at the Udmurt State University (the Western Cis-Urals), together with industrial partners, a research and production site (RPS) was created for the development and testing of technologies for recycling organic waste using insects, and (hereinafter referred to as the RPS). During this period technical specifications were developed and registered for the production of two products of biorecycling of organic waste by H. illucens larvae (feed for unproductive animals – dogs, cats, chickens, geese, ducks, pigs) and vermicompost enriched with beneficial microflora (Erickson et al., 2004; Liu et al., 2008; UdSU is a priority…, 2021). Scientific research has been carried out on the use of dried maggots to feed calves. The experimental design included: the 1st group was the control one (calves from 1 month old, had normal diet, without feeding with larvae); the 1st group was Experimental one (calves from 1 month old, had a feed additive of dry larvae); the 2nd group was the control one (calves from 3 months old, had normal diet, without feeding with larvae); the 2nd group was the experimental one (calves from 3 months old, had the feed additive of

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dry larvae). There were 5 observed animals in each group. The duration period of the experiment was 3 months. The schedule for introducing feed additives into the diet of calves is presented in Table 2.

Table 2. Schedule For Introducing the Feed Additive of the Dry Hermetia Illucens Larvae into the Diet of Calves of the Experimental Groups

The 1st Experimental group – calves from 1 month old		
from 1 to 2 month old	from 2 to 3 month old	from 3 to 4 month old
70 gr per 1 animal	100 gr	130 gr
The 2nd Experimental group – calves from 3month old		
from 3 to 4 month old	from 4 to 5 month old	from 5 to 6 month old
130 gr	150 gr	200 gr

Results

The results of the experiment on measuring the weight of calves are shown in Table 3.

Table 3. Weight of Calves in The Experiment on The Introduction of The Dry Hermetia Illucens Larvae into the Diet, Kg

Before the experiment	In 1 month period	In 2 months period	In 3 months period
The 1st control group			
39.58±3.29*	45.52±3.64	52.68±3.76	60.08±4.00
35.50... 43.66	41.00…50.04	48.01…57.35	55.11…65.05
The 1st Experimental group			
42.10±3.96	53.88±1.74	59.74±1.167	67.44±1.09
37.18…47.02	51.72…56.04	58.29…61.19	66.09…68.79
The 2nd control group			
80.76±3.16	84.30±2.16	89.22±2.31	93.76±2.33
76.84…84.68	81.62…86.98	86.36…91.08	90.87….96.65
The 2nd experimental group			
82.54±3.68	88.80±0.40	93.24±1.15	98.52±0.26
77.97…87.11	88.30…89.30	91.81…94.67	98.20…98.84

Note. Mean value ± standard deviation is indicated; confidence interval for the mean value, at $p<0.05$

In the first experimental group, the month after the start of feeding calves with larvae, a significant increase in body weight was observed compared to the control group. Similar results were obtained in the second experimental group. In addition, in the experimental groups the calves did not have diarrhea, the coat was smoother, there were no bald spots, and the animals were more active than in the control group.

Feeding rations for the H. illucens larvae themselves are being developed at the research and production site. The research and production site plans to develop and test technologies for recycling a range of organic waste, including agroindustrial waste, such as waste from brewing, dairy production, meat production and other industrial waste.

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The biochemical analysis of the resulting larva was carried out: 48% protein easily digestible by animals with all essential amino acids; up to 40% fatty acids; mineral elements 5.4%; chitin – 4.2%; melanin (up to 0.3%).

Table 4 shows the amino acid composition of the proteins of the H. illucens larva, as well as the fatty acids it contains.

Table 4. Percentage of Amino Acids and Fatty Acids in the Hermetia Illucens Larva

Amino acids	Content, %
Alanine	2.78
Arginine	1.92
Aspartic acid	3.76
Valin	1.92
Histidine	1.35
Glycine	2.24
Glutamic acid	4.72
Isoleucine	1.43
Leucine	2.60
Lysine	2.37
Methionine	0.68
Proline	2.76
Serin	1.72
Tyrosine	2.44
Threonine	1.70
Phenylalanyl	1.54
Cystine	1.07
Fatty acid	Content, %
Lauric	49.6
Palmitic	10.6
Oleic (omega-9)	18.46
Linoleic (omega-6)	22.88

Discussion

At present, global warming is observed (Vedernikov et al., 2022; Costa et al., 2023; Schillerberg, Tian, 2024). In a number of regions, warming has led to destabilization of weather conditions (Larionov et al., 2020a; Slavskiy et al., 2023; Yuan et al., 2024), to climate aridization (Larionov et al., 2020b, 2023; Mazina et al., 2023; Iyiola et al., 2024; Kalfas et al., 2024). Disturbances in natural and cultural landscapes are increasing. Global warming initiates recycling of degradation of agricultural landscapes (Volodkin et al., 2021; Sharma et al., 2024; Yin et al., 2024). Overall, the world is experiencing land alienation (Azadi et al., 2021; Pogibaev, Larionov, 2024), disruption of development and loss of crop yields (Prajapati et al., 2024), a decrease in the bioproductivity of agricultural and urban forests (Soto, Visseren-Hamakers, 2018; Ljiljana et al., 2021; Slavskiy et al., 2024), and a weakening of ornamental and greenery plantings on agricultural, populated and industrial lands.

With the weather and climate changes, the need for greening nature management has become especially obvious: in agriculture, in the agro-industrial complex as a whole, in suburban and urban crop production, in livestock farming, in agro-feed and agro-food production. There is a need to modernize the management of agricultural organic waste. By introducing closed agricultural management (Wani et al., 2017; Van der

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Velden et al., 2021; Gholipour et al., 2024; Mateo et al., 2024; Toplicean, Datcu, 2024) it is necessary to satisfy the growing crop and livestock needs, slow down and eliminate the loss of soil resource properties and improve their condition. In addition, the feasibility and usefulness of involving organic plant and mixed urban waste in biorecycling and using it in agricultural plant growing and land reclamation to achieve economic goals and carbon sequestration are being actively discussed (Xiang et al., 2022; Mateo et al., 2024), for the ecological stabilization of geochemical cycles in cultural ecosystems and landscapes, for the stabilization of biogeochemical relationships between biotic, bio-inert and abiotic components of created cultural ecosystems. This is necessary in a complex manner when transforming climate and agricultural landscapes, including as a result of economic activity.

One of the most effective greening directions in this aspect is the use of valuable biomaterials from biological recycling of crop (Gholipour et al., 2024; Türkten, Ceyhan, 2024), mixed agricultural (Nath et al., 2023; Menon et al., 2024), livestock (Van der Velden et al., 2021; Wang, Cui, 2024), food and

agro-food (Xiang et al., 2022; Diniso et al., 2024; Gholipour et al., 2024), and other types of organic waste (Van der Velden et al., 2021). Such biomaterials are suitable for use by plant growing, livestock breeding, resource conservation and reclamation institutions, as well as recycling, food and other enterprises. By the way, biomaterials from the recycling of agricultural waste are applicable for the variety of applications, including the effective absorption of pollutants (Monica et al., 2023). Moreover, the volumes of organic waste in the agricultural sector (Vivallos Soto et al., 2022; Nath et al., 2023; Toplicean, Datcu, 2024; Sihlangu et al., 2024; Wang, Cui, 2024) and urban areas (Nath et al., 2023; Mateo et al., 2024) in different regions of the world are increasing annually. It is discussed (Cao et al., 2024; Dagoudo et al., 2024; Menon et al., 2024) that many problems can be solved by climate projects for decarbonization of agricultural farming.

These programs should also be oriented toward obtaining high-quality and environmentally safe organic agricultural products. At the same time, the question (Vastola et al., 2023; Cao et al., 2024; Chu et al., 2024; Gandhi et al., 2024; Urechescu et al., 2024) remains open about the economic feasibility of the approaches used to the biorecycling of organic waste and subsequent use. The use of biorecycling products in agriculture (Vivallos Soto et al., 2022; Adefeso, Isa, 2023; Kundius, Bayarsukh, 2023; Radović et al., 2023; Kolawole et al., 2024), in urban and agricultural crop production, food and the agro-food industry (Ajila et al., 2011; Karani et al., 2021; Rawat et al., 2024) continues to be considered labor-intensive and not economically attractive enough.

In our case, the example of the solution to the complex ecological-economic and ecological-climatic problem of recycling organic agricultural waste for agriculture (and for related areas of nature management) is shown. The scientific group of the RPS developed the climate project to create five enterprises in the Western Cis-Urals for the biorecycling of organic waste as part of municipal solid waste. In Udmurtia there are five landfills for solid household waste; 770 thousand tons of organic waste are generated annually, incl. agro-industrial waste – 230 thousand tons/year. At the same time, greenhouse gas emissions amount to 2 million tons of CO2-eq/year (agro-industrial waste – 590 thousand tons of CO2-eq./year. With the increase in economic importance and the intensification of agriculture, the formation of plant and livestock waste will increase. Accordingly, the ecological and climatic problem may persist.

In general, in the East European Plain (Shaikhiev et al., 2020; Pilarska, Pilarski, 2023), in other regions of Eurasia (Shi et al., 2017; Wang, Cui, 2024; Yadav et al., 2024) and the world (Xiang et al., 2022; Hamrouni et al., 2023; Karimi et al., 2024; Siddiqui et al., 2024), there is now an obvious tendency towards an exacerbation of this complex problem in the agricultural and food sectors, and in other economic complexes associated with them. There is a potential danger of limiting the resource capacity of cultural landscapes and agroecosystems, losing their bioproductivity and environmental sustainability, and weakening the reproduction of the resource base. Against the background of global warming and in many regions of climate aridization, there is a threat of disruption and destruction of soil biota. The danger of destruction and degradation of soil and vegetation cover, loss of their bioecological properties are relevant.

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The global trend towards greening land use has been adopted, including through enriching soils with vermicompost (Gill et al., 2023; Gholipour et al., 2024; Islam, Raihan, 2024). The rising cost of feed and feed additives (Marak et al., 2024), including those of plant origin (Khair et al., 2024), for agricultural and domestic animals shows the relevance of finding affordable, high-quality raw materials. It is indicated (Khair et al., 2024; Sumartono et al., 2024) that, as the raw material, priority should be given to biomaterials from the biological recycling of organic agricultural waste.

Calculations showed that the cost of building the plants would be 900 million RUB (11 million USD). Waste recycling capacity is 120 thousand tons/year. The economic effect will be: carbon units 180 thousand tons of CO2-eq./year (170 million rubles/year or 2.0 million USD/year); production of larvae (4.4 million RUB/year or 52 thousand USD/year) and vermicompost (2.55 million RUB/year or 30 thousand USD/year). The payback period will be 5.2 years.

The sales market for finished products can be the agricultural sector (vegetable growing, livestock

farming, poultry farming, plant growing and vegetable growing), small and large household plant growing farms (garden plots and cooperatives, vegetable plots, various front gardens), greenhouse and flower farms, plant nurseries, fisheries, pet owners, as well as the area of reclamation of organic waste formation sites and landfills, urban construction and landscaping, reclamation of disturbed and contaminated soils. Market volume: feed additives market: 5 million t/year (20 billion RUB) (deficit 1.8–2.1 million tons/year – 40% of the market) ("On amendments to the Federal Scientific and Technical Program development of agriculture for 2017-2025", Decree of the Government of the Russian Federation of September 3, 2021 No. 1489). Vermicompost market: 1.5 million tons/year (40 billion RUB) (shortage 1.0 million tons/year). Development forecast – 20% growth of the vermicompost market, feed additives – 30%.

The diagram of the planned business process is presented in Figure 3.

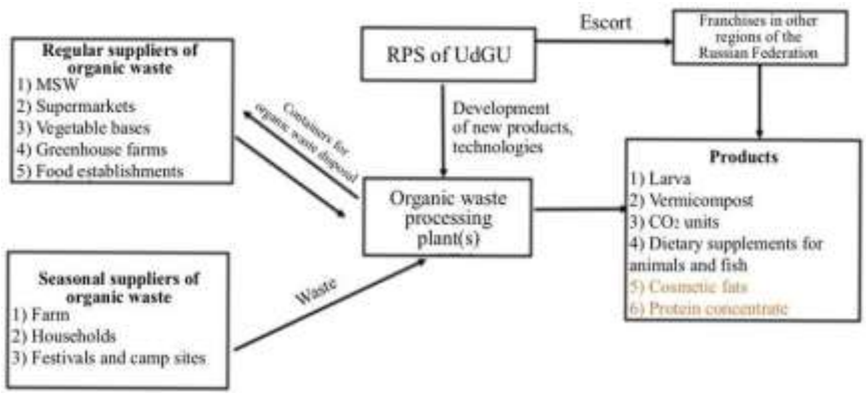

Figure 3. The Diagram of the Planned Business Process

The analysis of possible risks of project implementation was carried out: 1. marketing, which lies in a narrow market segment. The solution option is to expand the product line; 2. economic risk, because this technology is not widely used in Russia. In connection with this, there is a lack of sustainable logistics supply chains for raw materials that would ensure the stable and regular functioning of the biotechnological complex. The solution is the creation of enterprises at collection points and landfills for organic waste, using the logistics of the already created infrastructure (or at large enterprises producing organic waste); 3. relative complexity of the technological cycle; 4. legal risk lies in a possible change in legislation (GOST). The solution is to quickly adapt and obtain a license. In addition, it is advisable to adopt regulatory requirements and regulations with an obligation for biological recycling of plant, livestock and other organic waste. Such obtained organic materials, including those obtained using H. illucens flies, must be involved

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in agricultural use to improve the ecological-resource and agronomic properties of soils, to increase the productivity of crop lands, livestock, agro-feed and agro-food production.

The need for organic and regenerative farming (Wani et al., 2017; Xiang et al., 2022; Abad, Shafiqi, 2024; Manzoor et al., 2024; Trand et al., 2024) is now evident worldwide. The potential for bioconversion of organic agricultural waste by means of common insects is not used. Or these potentials are used very limitedly. Vermicompost from plant waste recycling by the H. illucens has improving and ecologically stabilizing properties in relation to soils and agrophytocenoses (Bashtovenko et al., 2023). The few studies indicate the potential for improving the ecosystem and economic qualities of agrolandscapes (Hu et al., 2023; Rampure, Velayudhannair, 2023; Diola et al., 2024) and other types of cultural landscapes using such vermicompost. Due to their natural qualities, the larvae of these flies perform sanitary and hygienic functions. They disinfect recycling biosubstrates (including waste) and soils, carry out bioremediation of heavy metals (Hu et al., 2023; Kofroňová et al., 2024), implement protection against soil pathogens, ensure the availability of nutrients in the soil, initiate ecological successions and improve the ecological properties of microbial biocenoses (Xiang et al., 2022).

Biorecycling products from organic waste (plant, livestock, agro-food, food, municipal, urban, etc.) by the H. illucens contribute to accelerated and improved humification (Xiang et al., 2022), increasing the resource qualities and health of soils (Xiang et al., 2022; Hu et al., 2023). Such biosubstrates are necessary to increase the productivity and sustainability of agroecosystems. This organic fertilizer is in demand to combat the destruction and degradation of agricultural lands and for their resource-ecological rehabilitation (Idris et al., 2024). This type of fertilizer is necessary to overcome the processes of depletion of degraded and alienated lands (Larionov, 2013; Galstyan et al., 2023; Kundius, Bayarsukh, 2023; Ngun et al., 2023; Larionov et al., 2024; Pogibaev, Larionov, 2024), lands of reclamation, landscaping and agricultural categories (Pogibaev, Larionov, 2024), in various settlements and in other diverse territories.

The vermicompost obtained through the recycling of organic waste by the H. illucens contributes to the growth of agricultural crop yields (Shaikhiev et al., 2020; Rampure, Velayudhannair, 2023; Idris et al., 2024), the sustainability and ecological functionality of nursery and garden-park phytocenoses and other plantings (Shaikhiev et al., 2020). Their use is advisable in connection with global warming and as a result of the aridization of weather and climate conditions in humid, subhumid, especially in semi-arid and arid regions.

Additionally, it is recommended to create phytomeliorative complexes (Veisov, Hamrayev, 2022; Hakimi et al., 2024), agroforests (Larionov et al., 2024; Slavskiy et al., 2024; Joshi et al., 2024; Zou et al., 2024) and ecologically protective landscaping compositions (Volodkin et al., 2022; Volodkin, Larionov, 2022; Larionov et al., 2024; Yuan, Kim, 2024; Zhang et al., 2024) near agricultural lands, near organic waste storage sites and recycling points, taking into account the terrain features, geological structure, soil and climatic, ecological and planning conditions of the area. It is important to select plant species and varieties with broad ecological valences (Volodkin et al., 2021, 2022; Larionov et al., 2023; Pogibaev, Larionov, 2024) to limiting abiotic, biotic and technogenic factors.

In landscaping and agroforestry plant growing, preference should logically be given to species of woody and herbaceous plants from the local flora (Davis et al., 2005; Khattak et al., 2017; Volodkin et al., 2022; Volodkin, Larionov, 2022; Larionov et al., 2023; Horvat et al., 2024). This is explained by their greatest adaptability to local weather, climate, geomorphological, hydrological and edaphic conditions. It is also necessary to control plantings and prevent bioinvasions (Davis et al., 2005; Larionov et al., 2021, 2024; Xiang et al., 2024) into neighboring natural ecosystems and agroecosystems. The same approaches are appropriate for the creation of phytocenoses from native and introduced plants with valuable properties (Lubimov et al., 2016; Larionov et al., 2018, 2021, 2024) for the phytoecological protection of territories for agricultural, agroforestry, food and agro-feed, soil protection and water protection purposes. These cultural phytocenoses will be focused on long-term functionality to reduce the pressure of abnormal weather and climate factors on agricultural crops and agroecosystems, to deposit carbon in soils and to protect them bio-wise. Taken together, ecological-protective and phytomeliorative plantings using products of biorecycling of organic waste will create conditions for improving the resource intensity and economic potential of agroecosystems, agrolandscapes and other types of cultural landscapes.

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The H. illucens larvae grown on biosubstrates from the biorecycling of organic waste represent an accessible food source for various agricultural (Hu et al., 2023; Sankara et al., 2023; Manyapu et al., 2024; Pradabphetrat et al., 2024; Tepper et al., 2024) and commercial (Bahri et al., 2023) animals. The prospects for the economic and industrial bioconversion of plant waste and waste from the recycling of plant food using the H. illucens larvae to produce feed and feed additives are mainly at the discussion level.

It is important that for the biological recycling of organic waste there is no shortage of the necessary volumes of plant materials (waste from crop farms, waste from the production and consumption of plant foods, waste from plant feed for animals, plant litter, etc.), waste from livestock farming and from mixed waste of plant and animal origin.

In various variants of application of products of biorecycling of organic waste using the H. illucens, acceptable economic (Larionov et al., 2018; Tepper et al., 2024; Urechescu et al., 2024), ecological (Xiang et al., 2022; Zulkifli et al., 2023; Diola et al., 2024; Pradabphetrat et al., 2024) and climatic effects (Shaikhievs et al., 2020; Xiang et al., 2022; Zulkifli et al., 2023; Urechescu et al., 2024) are achieved. It is precisely as the complex ecoclimatic and economic project that our development is universal for agriculture, urban nature management and related areas of social production, for the implementation of ecological and climate management in the handling of organic waste. In our case, this is shown using the example of the moderate continental climate of the East European Plain (in the Western Cis-Urals). According to the International Standard for Agricultural Purposes (Oduro-Kwarteng et al., 2018), the products of biorefining of plant and mixed organic agricultural wastes meet international requirements for commercial organic fertilizers.

Accordingly, the implementation of our development will contribute to the growth of resource intensity and productivity of agroecosystems, and improvement of the quality of agricultural products. There is the opportunity for close ecological and economic integration of crop production, recycling of agricultural products and livestock farming. Such integration generally applies to the agro-industrial complex and to the areas of agricultural nature management, environmentally friendly handling of agricultural, agro-feed and agro-food waste.

Plant growing can act as a supplier of organic raw materials for biorecycling and for subsequent involvement in agricultural and production cycles. Also, crop farms will have the opportunity to receive affordable organic fertilizers. Animal husbandry can act not only as an independent branch of agriculture, but also as a collective subject of consumption of products from the biorecycling of organic waste. Consequently, conditions are created for the integration and synergy of crop and livestock production in solving economic problems and maintaining the sustainability and emergence of agroecosystems. This is promising in the ecological-economic and ecological-climatic sense. This is the effective tool for ecoclimatic and eco-agroeconomic management, ecologized management of complex agricultural nature management on a low-waste and waste-free basis.

Due to their wide distribution (Oduro-Kwarteng et al., 2018; Ushakova et al., 2018; Shaikhiev et al., 2020; Shaikhievs et al., 2020; Surendra et al., 2020; Bastrakov, 2023; Pestsov et al., 2023; Rampure, Velayudhannair, 2023; Sankara et al., 2023; Diola et al., 2024), bioecological and ecological-economic features (Oduro-Kwarteng et al., 2018; Nekrasov et al., 2019; Shaikhievs et al., 2020; Surendra et al., 2020; Asylbekova et al., 2022; Bastrakov, 2023; Hu et al., 2023; Pestsov et al., 2023; Diola et al., 2024), the H. illucens can be involved in biotechnological and ecoclimatic programs. Reducing greenhouse gas emissions, sequestration and deposition of organic carbon, bioecological stabilization of its cycle and the cycle of other biogenic elements allows us to solve many subsequent landscape-ecological, nature-preserving, crop and livestock problems, establish closed agriculture, agro-industrial and processing complexes.

This species is now the cosmopolitan. It seems realistic to use individuals of this species to solve agricultural problems in the corresponding regions of the world and even more widely due to the natural possibility of sustainable reproduction and development in a secondary habitat and in production conditions. This allows their practical and industrial use in the biorecycling of agricultural and agro-food waste in laboratory and production conditions. It is advisable to scale up such experience in different territories. The development

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is especially valuable in various climate manifestations and in different states of agroecosystems. The real possibilities for economically accessible biorecycling of waste are obvious, even against the backdrop of global changes in weather and climate factors in different regions of the world. Such ecological and climatic programs can be implemented in Russia, Europe, the Caucasus, China and other territories of the East Asia, the Southeast and South Asia, the Central and Southwest Asia, Oceania, Africa, the Central and South America, etc. It is necessary to train personnel in the areas of biological recycling of plant, agro-food and other types of organic waste due to the relevance of this interregional and global problem, landscape and ecological usefulness and economic feasibility. The work also has great scientific and educational value as the reference and educational material for students studying agronomy, soil science, agroclimatic, agrochemical, biological and environmental specialties, as well as greening waste management, geosciences, economic sciences and ecoclimatic management.

Conclusions

Thus, we believe that recycling organic waste using the Hermetia illucens larvae is a universal ecological-climatic biotechnology that reduces greenhouse gas emissions, in the future they will amount to 180 thousand carbon units per year. With regard to five organic waste landfills, the efficiency of their biological recycling will be 120 thousand tons/year. This technology not only reduces waste and reduces the negative impact on the environment, but also produces valuable products such as organic fertilizer for crop farms, for greening complexes in cities, towns and villages, for complexes on phytomeliorative and agroforestry reclamation forestry, greening of cities, towns and villages, and feed additives for farm animals. The presented ecoclimatic project has universality in content and applicability in many regions of the world.

Many areas of the world, including the East European Plain (and, for example, the Western Cis-Urals) have high potential for secondary raw materials for the development of the economic sector for recycling waste and obtaining secondary raw materials or products based on them. This is necessary for crop and livestock complexes, for urban, suburban and rural areas. Our ecoclimatic project solves the problems of increasing resource capacity, productivity and sustainability of agroecosystems. In particular, the production of vermicompost will require 30 thousand USD (taking into account the recycling of organic waste from five landfills). Payback is possible within the five-year period. The needs of the vermicompost market (even with growth of 20% or more) and feed additives (with growth of 30% or more) are met.

In this way, it is possible to improve systems for handling organic waste and managing land use, agricultural, food, agro-feed, communal and related economic complexes. This universal biotechnology is aimed at the rational and ecologically-hygienically safe use of agricultural bioresources, waste from their recycling and use: plant waste, plant litter, waste from the processing and use of agricultural products, other types of organic waste and related biomaterials.

The use of the H. illucens larvae in the recycling of organic waste makes it possible to develop the field of environmentally friendly waste recycling, which can partially offset costs through the sale of by- products.

In the process of work, the effectiveness of using the H. illucens larvae to solve the problem of recycling organic waste was substantiated, the expected market for finished products obtained from recycling organic waste was analyzed, and the risks of the project and its benefits were assessed.

The analysis of the biotechnology for recycling organic waste using H. illucens larvae showed the feasibility of this project, which has prospects for further development and registration as the ecological- economic and climate project. This type can be considered as the sustainable and functional tool for biorecycling of plant, livestock, food, municipal and other organic waste. The availability of ecosystem services provided by agricultural landscapes and agricultural production facilities is increased based on the considered nature-like technology. This makes it possible to ensure the involvement of organic waste in subsequent agricultural use and to rationalize nature management. Our example of biorefining of agricultural, municipal and industrial organic waste can be considered as the best available nature-like technology with obvious environmental, climate and economic efficiency. It is advisable to implement and scale it up in different economic areas. The idea and material of our development can be used in different regions of the world using the H. illucens and other organisms with similar biological and ecological characteristics.

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A.S.P., A.G.K., M.V.L., N.A.I., A.S.B., T.A.Z. and S.A.B.; data curation and analysis, I.L.B., A.S.P.,

A.G.K., M.V.L. and N.A.I.; writing – original draft, I.L.B., A.S.P., A.G.K., M.V.L. and N.A.I.; Writing – review and editing, I.L.B., A.S.P., and M.V.L; organizational conceptualization and administrative support, I.L.B. and M.V.L.; participation in revision, I.L.B., M.V.L. and A.S.P.; visualization, A.S.P., A.G.K., N.A.I., A.S.B., T.A.Z. and S.A.B.; project design, I.L.B., M.V.L. and

A.S.P. All authors have read and agreed to this version of the manuscript.

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