

HUMIC FERTILIZATION: SOIL REGENERATIVE CONSIDERATIONS

Gheorghe JIGĂU, Sergiu DOBROJAN, Galina DOBROJAN

Scientific Research Center "Natural Science Integrity", Moldova State University,
59 Al. Mateevici Street, Chisinau, Republic of Moldova

Corresponding author email: gheorghe.jigau@gmail.com

Abstract

Based on a synthetic analysis of our own and other research, the opportunity to use humic fertilization in order to stop the degradative trend characteristic of arable chernozems and regenerate the chernozem process is argued. Through the perspective of the biophysical concept of the chernozem process of pedogenesis in the present research, the regeneration of the humification process, which constitutes the essence of the chernozem process of solification, is examined based on the direct and indirect action of humic fertilizers on the functionality of the "plant-microbiome" system in the rhizosphere. It has been established that the use of humic fertilizers, as biologically and physiologically active substances, contributes to the biostimulation of the "plant-microbiome" system and the catalysis of the humification processes that occur in the rhizosphere under their interconnected action. The evaluation of the pedoregenerative efficiency based on the cellulolytic activity, the microbial biomass content, the fractional composition of humus and the agrochemical fertility indices highlighted the intensification of the cellulolytic activity in the humuso-accumulative horizon by 10-14%, the increase by 3-12% of the microbial biomass in the 0-40 cm layer, manifested in the intensification of the humification process. It was established that the regeneration of the humification process involves two distinct stages: a) primary humification (the active biological period April-June) with the formation of "young" humic substances of easily mineralizable humic nature and b) secondary humification with the formation and stabilization of stable humic substances of humic nature. The regeneration of the humification process led to the optimization of the soil nutrient regime.

Key words: fertilization, chernozem pedogenesis, humificatic fertilization, rhizosphere, plant-microbiome system, soil regenerative processes.

INTRODUCTION

The synthetic analysis of the effects induced by the current technologies promoted, including by FAO, for the purpose of regenerating typogenetic processes in arable chernozems has shown that they can only ensure a slight restoration of humus reserves (about 10% of the lost quantities) and of the structural aggregate state related to the humification process (Jigău et al., 2022). In this context, we consider that the technologies practiced, although they have sufficient bioenergetic potential for the initiation and unidirectional development of chernozem typogenetic processes, ensure only partial achievement of this due to the advanced degree of physical degradation (Jigău, 2023). Through this prism of ideas, we consider that in the arable chernozems of the region, in a relatively short period of time (about 100 years), very profound changes have occurred in their physical state, which have entailed such significant changes in the soil biota that it is no longer able to support the humification of fresh organic matter and the

accumulation of biophilic elements in the arable horizon. This implies the conclusion that within the natural chain of substance transformations, some links of it, for which certain groups of living organisms are responsible, have formed "weak spots" that limit the intensity of pedogenetic/typogenetic processes (Larionov, 2013). In this regard, research has shown that in the arable layer of arable chernozems, the number and mass of microorganisms increases and the number and mass of pedomesofauna significantly reduces (Larionov et al., 2013). As a result, in arable chernozems, the processes of transformation of plant residues are intensified and the mineralization energy increases approximately twice.

This leads to the disruption of the natural balance between the mineralization and humification processes characteristic of natural ecosystems, manifested in the increase in the share of mineralization processes (Kokovina, 1988). This being the main factor that led to the direction of the evolutionary trend of chernozems in a degradative sense (Jigău et al.,

2023). As a result, the intensification of the degree of suppression of some components of the pedocenosis led to the transfer of the soil ecosystem to a lower ecological-energetic level within which pedogenetic processes are carried out in narrower intervals of the values of physical and chemical parameters. This entails an increase in the vulnerability of arable chernozems to climate change (drought, excessive temperatures) and a unidirectional reduction in the self-reproduction process of chernozem pedogenesis (Jigău & Lesanu, 2021). In addition, the regeneration of the pedogenetic process within such technologies requires a long period of time. At the same time, both in our research and in other research, it has been established that the practice of technologies based on the use of liquid humic substances as biostimulators of processes occurring in the soil-plant system and as catalysts of the humification process contributes to the acceleration of biological and biochemical processes in arable chernozems and the regeneration of the pedogenetic process.

Conceptual-methodological considerations

In the literature, humus-based processes are considered as carbon-rich organic amendments in the form of humic substances extracted from manure, compost, crude and extracted forms of lignite, coal and peat (Lumactud et al., 2022). Humic substances are widely used with a market value exceeding 532.7 million dollars in 2021 and a projected growth rate of approximately 11.8% between 2022 and 2028 (Pulidindi & Prakash, 2021). In addition, for several decades, humic substances have been widely reported to improve soil health and crop productivity (Guo et al., 2019; Nardi et al., 2021). At the same time, numerous studies have demonstrated positive responses of soils and crops to humic substances from various sources in protected areas, open field and controlled environment studies (Rose et al., 2014; Yang et al., 2021; Bezuglova & Klimenko 2022). Ampong et al., recently provided a comprehensive analysis of the significant positive impact of humic acids on crop plant growth, yields and soil physical and chemical properties. Plants are more stress tolerant, more productive, healthier and produce better quality crops in soils with a high content of humic acids (Ampong et al., 2022).

Despite the above, the concept of humic fertilization, to date, faces a number of ambiguities. In this chapter, we mention, in particular, that, in most cases, in the literature in the field, the action of humic substances on the soil is confused with the action of humic substances formed within the continuum process of humification of fresh organic matter in the soil. In this context, in our research, humic substances used in modern agriculture are divided into two groups: a) humic fertilizers and b) humic fertilizers.

Within these, humic fertilizers are considered to be substances that represent the solid fraction of humic nature obtained within an accelerated humification technology of an organomineral substrate, made up of various zootechnical and vegetable wastes, with additions of industrial wastes from the sugar and thermoelectric industries and nitrogen-fixing cyanophyte algae *Chlorella* based on the natural humification model. Humic fertilizers are considered liquid humic substances resulting from accelerated humification within the same technology separated from the solid fraction by periodic decantation without the use of alkaline materials for extraction. In this paper, the principles of using humic fertilizers are fundamental and the effects induced by them on the functioning of the soil-plant system and the processes that occur in the rhizosphere are evaluated.

From the perspective of the biophysical concept of the pedogenetic process, their use is based on their action, as biologically and physiologically active substances that involve biostimulation of the processes that occur in the "plant-microbiome" system and catalysis of the processes that occur in the rhizosphere under their interconnected action.

Through this prism of ideas, the theoretical conceptual framework of humic fertilization is provided by the concept of the unity of the "soil-plant" system (Popov, 2012; Zelenskaya & Kerzhentsev, 2013).

The structural-functional unity of the plant and the soil within the ecosystem is based on metabolism, which includes the cyclical alternation of two processes: the synthesis of organic matter through photosynthesis with the assimilation of mineral elements from the soil by autotrophic organisms and their destruction by heterotrophs. In this sense, the soil, as a

component of the ecosystem, performs a very specific function within it and has its own unique mechanism for such a function, which is part of the mechanism of functioning of the ecosystem. Through this prism of ideas, the ecosystem is a symbiotic unit of biocenoses, specialized in types of nutrition (phytocenosis, zoocenosis, pedocenosis) integrated through a common closed metabolic circuit. Within it, the soil is considered a functional component of the ecosystem-saprotrophic biological community (pedocenosis) that functions synchronously with the phytocenosis, providing it with the necessary conditions (corresponding to landscape conditions) for the production of biomass. In response, plants return organic matter to the soil, ensuring the unidirectional implementation of the pedogenetic process (Zelenskaya & Kerzhentsev, 2013). In this sense, plants and soils form a unique trophic system and the basic functional mechanism of the “soil-plant” system involves quantitatively and qualitatively balanced reciprocal bilateral relationships between soil and plants, within which the basic functional link is the soil organic matter (Popov, 2012).

According to more recent research, the mechanisms of action of humic substances through plant-microbiome associations on pedogenetic processes that occur in the active root layer can be divided into two conventional groups: a) direct - direct stimulation of plant development and growth through the synthesis of growth stimulants (phytohormones and other metabolites) and improvement of plant nutrition; b) indirect stimulation of plant development and growth by suppressing the development of microorganisms (microscopic fungi and bacteria, phytopathogens) in the active root layer (Rajkumar et al., 2009; Fahad et al., 2014).

Direct stimulation of plant development and growth

The formation of phytohormones, vitamins and other biologically active substances by bacteria is an extremely important mechanism of interactions within bacterial-plant associations. It is known that plant development and growth is regulated by phytohormones, especially auxins, cytokinins, gibberellins, etc. Auxins stimulate the development of the root system, regulate organ differentiation, etc. Cytokinins induce cell division, increase seed germination, have a

beneficial effect on plants in unfavorable conditions for their growth and development (salt content in quantities exceeding the toxic threshold, pesticides, negative temperatures, drought, heat waves, etc.). Gibberellins are synthesized, predominantly, in leaves and systematize plant growth, accelerate seed germination.

The production of phytohormones is characteristic of practically all rhizobacteria, providing them with conditions for their own development as well as the establishment of relationships with plants and other microorganisms in the soil (Morgun et al., 2009; Shaposhnikov et al., 2011; Lankina et al., 2013; Afzal et al., 2014).

The intensification of humification processes under the catalytic action of humic fertilizers is accompanied by the formation of physiologically active humic substances that are characterized by a structural composition similar to natural phytohormones in the process of lignin transformation. In this regard, through the concept of staged humification of organic matter (Александрова, 1980; Komarov et al., 2017).

The sustainability of the functioning of the [plant]↔[microbiome] system supports the humification process by intensifying the biological nitrogen cycle. In this context, it is considered that rhizobacteria compensate for the losses of photosynthesis products (3-50%) consumed in the formation of root exudates and rhizodeposits (Umarov et al., 2007; Umarov, 1986).

According to the authors cited in the rhizosphere, in any pedoclimatic conditions, in the soil, processes of associative nitrogen fixation are carried out with the participation of several genera of *Arospirillum*, *Azotobacter*, *Acetobacter*, *Enterobacter*, *Pseudomonas*, *Bacillus*, *Clostridium*, etc. which form with plants integrated multicomponent systems with new features determined by the interactions between "partners" (plant-microorganisms) (Bukharin et al., 2007). At the same time, it has been established that the process of photosynthesis and nitrogen fixation are functionally interconnected (Isobe et al., 2014). In this regard, it has been established that the beneficial action of associative nitrogen-fixing rhizosphere bacteria on plants is based on a complex of interacting properties: nitrogen

fixation, secretion of physiologically active substances that stimulate growth, antagonism for phytopathogenic fungi and bacteria (Klopper et al., 1989).

According to more recent research, about 80-90% of soil bacteria have the ability to fix nitrogen (Turner et al., 2013). At the same time, it has been established that mixed populations of microorganisms develop in the rhizosphere, in which, along with nitrogen-fixing species, pectin- and cellulolytic species develop, forming an integral polycomponent system in which nitrogen-fixing species use (products from the decomposition of polymers, providing them with the nitrogen necessary for their decomposition. As a result, the interactive realization of the intercalated decomposition process of organic polymers (source of organic carbon) and that of nitrogen fixation (source of biological nitrogen) materialized in the intensification of the humification process is intensified. The continuous formation of fresh humic substances contributes to the intensification of the structural aggregation process by ensuring an optimal framework for the functioning of the soil-plant-biota-soil system. In this context, we mention that research has shown that during vegetation, as plants develop, the composition of root exudates and rhizodeposits changes, which is reflected in the formation of bacterial associations (Dobrovol'skaja et al., 2002).

At the same time, the amount of microorganisms also changes - the rhizosphere effect increases starting from the "seedling" phase to the maximum in the flowering and fruit formation phase (primary humification stage) in the subsequent phases (secondary humification stage) the rhizosphere effect decreases.

At the same time, the distribution of rhizobacteria in the rhizosphere is not homogeneous: in larger quantities they are contained in the econiches of young roots where maximum quantities of soluble root exudates are secreted. In the spaces related to mature roots, hydrolytic bacteria have a greater development (Dobrovol'skaja, et al., 2002). This implies the conclusion that under conditions of permanent plant coverage in the rhizosphere, humification processes materialized in aggregation (sequestration of organic carbon) and structuring (stabilization of organic carbon) are

constantly taking place. Through this prism of ideas, the interdependent and interdetermined development of the process of formation-accumulation of humus and of aggregation-structuring represents a continuum of rejuvenation of the humus state and the structural-aggregate state, materialized in the constitution and functioning of the genetic-evolutionary system [humic system]↔[aggregate system] responsible for the reproduction of the chernozem process of solification.

Humification is also favored by the intensive mobilization in the rhizosphere of phosphorus but also of other biophilic elements related to the organic carbon cycle as well as the humus formation process.

In this sense, we consider that the efficiency of humification depends not only on the amount of fresh organic matter in the soil but also on the content of other biophilic elements (about 32 elements), especially the C:N:P:S ratio. In the case of chernozems, phosphorus is one of the factors that limits the efficiency of the humification process.

The microflora of humic preparations influences the phosphorus cycle by modifying the absorption of phosphorus by plants: 1) providing a source of organic phosphorus; 2) intensification of the microbial activity of the soil biota that solubilizes phosphorus; 3) local increase in soil acidity in the rhizosphere as a result of the intensification of the transformation process of organic acids (malic, acetic, citric, etc.) and humic acids (which have pH values < 3.8); 4) increased availability in the soil through the formation of insoluble organo-mineral compounds with metal ions (Al^{3+} , Fe^{3+} , Ca^{2+} , Mg^{2+} , etc.) (Jindo et al., 2020).

Indirect stimulation of the functioning of the "plant-microbiome" system involves the ability of plant growth-stimulating bacteria to suppress phytopathogenic microorganisms - microscopic fungi and bacteria (Chowdhury et al., 2015). Growth-stimulating bacteria suppress the growth and development of pedophytopathogens, thus minimizing their impact and contributing to the normal growth and development of plants. At the same time, they contribute to the aggregation-structuring of the soil mass and the optimization of the pedofunctional environment.

MATERIALS AND METHODS

The research was carried out under production conditions on typical moderately humus-rich clayey-loamy chernozems using the NEOFERT-M humic fertilizer of local origin obtained within a technology based on the natural model of controlled composting-humification of an organomineral substrate made up of various wastes of zootechnical, vegetable, industrial origin (from the sugar, bakery, thermoelectric industries) with additions of green algae (*Chlorella vulgaris*). The technology practiced involves treating the

substrate with a NEOFERT-M+*Chlorella* fertilizer mixture, composting it on the soil surface (4-6 weeks), and subsequently incorporating it into the humus-accumulative horizon by alternating the humification depth over time. During the vegetation period, 3 treatments with the NEOFERT-M+*Chlorella* mixture were carried out in the key phases of crop development.

The soil regenerative efficiency was assessed based on agrochemical fertility indices, fractional composition of humus, microbial biomass content and cellulolytic activity.

Table 1. Dynamics of agrochemical fertility indices of moderately humiferous chernozems under conditions of composting-humification of organic matter in the upper soil horizon (layer 0-30 cm)

Date of soil sample collection	Culture	Agrochemical fertility indices				
		pH	Humus, %	mg/100 g of soil		
				N-NO ₃	P ₂ O ₅	K ₂ O
13.06.25	Control	7.40	3.38	0.63	2.39	25.16
	Sunflower	7.21	3.84	0.94	4.89	26.68
	Winter Peas	7.21	3.89	0.77	4.28	21.38
	Corn	7.18	3.92	0.97	4.43	24.44
10.09.25	Control	7.52	3.24	0.58	2.47	24.31
	Sunflower	6.53	4.32	0.67	3.88	18.74
	Winter Peas	6.39	4.21	1.15	3.78	26.27
	Corn	6.29	4.21	1.15	6.22	22.12

In the initial phase, the soils in the experimental plots are characterized as weakly basic (pH = 7.47-7.53) and differ insignificantly from the control variant (pH = 7.48). During the active biology period of the following year (13.06.2025) the pH values are reduced insignificantly, presenting values within the neutral range, detaching insignificantly from those characteristic of the control variant (Table 1). During the second half of the vegetation period (June-September) the pH values in the soils in the experimental plots are reduced and fall within the weakly-acid range (pH < 6.50). At the same time, in the control variant, the soil reaction is weakly basic (pH = 7.52). This allows us to consider that the dynamics of the soil reaction is determined by organic acids (malic, citric, acetic, etc.) and humic (humitic and fulvic) originating from the humification process. Indispensable for these processes is also the increase in the content of N-NO₃

contained in the newly formed humic substances. Acidification of the soil solution contributed to the establishment in the soils of a stable trend of increasing the content of mobile phosphorus. At the beginning of the 2025 vegetation period, its content exceeded the content in the control variant by about 1.8-2.0 times. At the end of the vegetation period, although part of the phosphorus was used in the formation of crops, its content was about 1.5-2.5 times higher than in the control variant. The potassium content remains relatively stable, establishing itself in the range of relatively optimal values.

The evaluation of the action of humic fertilization on the soil microbiome based on microbial biomass shows that, already in the first year of fertilizer application, it contributes to an increase in its quantity compared to the control and to the relative stabilization of biomass during the vegetation period (Table 2).

Table 2. Microbial biomass of typical chernozem under controlled composting-humification technology conditions during the active biology period (13.06.2025)

Culture	Depth, Cm	Microbial biomass (BM) mg C/g soil	C _{BM} % of C _{total}	BM reserves kg/ha	
				in layers	in layers 0-40 cm
Control	0-30	170.2	1.01	1665.3	1884
	30-40	163.5	0.60	209.0	
Sunflower	0-30	270.7	1.17	1884.1	2254.8
	30-40	168.5	0.63	370.7	
Winter peas	0-30	269.4	1.18	1503.3	1940
	30-40	234.9	1.03	436.9	
Corn	0-30	227	1.89	1539.7	2059.8
	30-40	224.2	1.87	520.1	

At the same time, a dependence of the amount of microbial biomass on the cultivated crop is clearly outlined.

In this sense, it is known that all crops have a direct impact on microbial biomass.

This action is determined by their ability to secrete root exudates that favor the formation of an optimal environment for the functioning of the "plant-microbiome" system.

In this sense, the action of foliar humic fertilization is achieved by intensifying the development processes of the root system on which the amount of exudates and their composition depend, indispensably. Through this prism of ideas, we find that among the crops cultivated in the experimental fields, sunflower and corn, due to their strongly developed root system throughout the thickness of the 0-40 cm layer, most significantly influence the amount of biomass produced in the soil during the vegetation period, this being reproduced continuously throughout the entire period of active functioning of the "plant-microbiome" system.

Pea culture produces a smaller amount of biomass, at the same time, but it is more qualitative since it is richer in biological nitrogen that contributes to the formation of more qualitative humic substances.

According to our previous research, foliar fertilization with humic substances is a factor that catalyzes the meaning and intensity of the humification process, being at the same time a carrier of the "genetic code of humic humification".

Monitoring the fractional composition of soil humus within the experimental plots showed that the humification process under controlled humification conditions under the action of humic fertilizers involves the achievement of the

stages of humification characteristic of uncultivated chernozems.

In this sense, the present research has shown that within the controlled humification process under the action of humic fertilization, two stages characteristic of the natural model of chernozem humification are clearly outlined: a) primary humification (April-June) characterized by the intensive development of the humification process with the formation of humic substances, predominantly of a "young" humic nature with a lower molecular mass manifested in the values of the Cah:Caf ratio >2 ; b) secondary humification that involves the polymerization condensation of newly formed humic substances and the stabilization of "mature" humic substances materialized in Cah: Caf values of about 2.

Primary humification is favored by the favorable temperature and humidity regime + characteristic of the April-June period.

The data in (Table 3) show that primary humification is influenced by the cultivated crop. More favorable conditions are provided by the autumn pea crop, which ensures the formation of a quantity of humic acids that exceeds by about 2.59 times the quantity of fulvic acids. In our opinion, this is due to the enrichment of plant biomass, especially root biomass, with biological nitrogen.

The formation of humic substances also occurs intensively in the case of corn, which, in our opinion, is due to higher amounts of carbohydrates (polysaccharides) in the composition of the exudates of this crop.

Secondary humification is favored by the hydrothermal regime specific to the dry period (July-August) which contributes to the dehydration of humic substances manifested in the polymerization-condensation of molecules

of "young" humic substances with the formation of stable substances with high molecular weight. Probably, the denitrogenation of humic substances also contributes to the realization of this process. The values of the Cah:Caf ratio at the end of the vegetation period testify in favor of this statement. From the data in (Table 3) we find

that its values are significantly reduced and make up 1.91 in the case of spring pea crop (reduction by 0.68) and 2.0 in the case of corn crop (reduction by 0.40). On the other hand, in the case of sunflower crop, the Cah:Caf values do not change, which allows us to assume that in its case more stable humic substances are formed from the start.

Table 3. Fractional composition of humus in the arable layer of typical moderately humiferous chernozem under controlled composting-humification technology in the upper part of the profile (layer 0-30 cm)

Date of soil sample collection	Culture	Humus content, %	Total carbon content (C _t), %	Carbon content, esterified with pyrophosphate+NaOH, %	Humic acid carbon content, %	Fulvic acid carbon content, %	Hydrolyzed carbon content, %	Cah: Caf
13.06.25	Control	3.36	1.95	<u>1.06</u> 54.35	<u>0.68</u> 34.87	<u>0.38</u> 19.49	<u>0.85</u> 51.64	1.78
	Sunflower	3.98	2.20	<u>1.36</u> 59.38	<u>0.91</u> 39.73	<u>1.45</u> 19.65	<u>0.93</u> 40.62	2.02
	Winter Peas	3.84	2.21	<u>1.22</u> 55.20	<u>0.88</u> 39.82	<u>0.34</u> 15.36	<u>0.99</u> 44.20	2.59
	Corn	2.06	1.18	<u>0.68</u> 57.62	<u>0.48</u> 40.68	<u>0.20</u> 16.95	<u>0.50</u> 43.68	2.40
10.09.25	Control	3.26	1.90	<u>1.00</u> 52.63	<u>0.61</u> 32.11	<u>0.39</u> 20.53	<u>0.90</u> 47.37	1.57
	Sunflower	4.21	2.42	<u>1.27</u> 52.48	<u>0.85</u> 35.12	<u>0.42</u> 17.35	<u>1.15</u> 47.51	2.02
	Winter Peas	4.32	2.48	<u>1.26</u> 50.80	<u>0.82</u> 33.03	<u>0.43</u> 17.39	<u>1.22</u> 49.39	1.91
	Corn	2.34	1.34	<u>0.71</u> 52.99	<u>0.62</u> 46.21	<u>0.31</u> 23.13	<u>1.00</u> 47.01	2.00

The administration of humic fertilizer contributes to the intensification of cellulose decomposition throughout the entire thickness of the humus-accumulative horizon by 10-14%, thus contributing to the intensification of the humification process (Table 4).

Table 4. Cellulolytic activity % of typical moderately humic clayey-loamy chernozems under controlled composting-humification technology conditions (13.08.2025)

Culture	Depth, cm	Variants	
		Control	Experimental
Sunflower	0-15	59.7	70.1
	15-25	67.1	70.3
Winter Peas	0-15	64.1	70.2
	15-25	59.6	71.0
Corn	0-15	62.2	71.7
	15-25	62.2	70.5

CONCLUSIONS

The unidirectional degradative trend of arable chernozems implies a specific approach to the regeneration of the chernozem soil formation process within the framework of controlled

humification technology by practicing humic fertilizers as biologically and physiologically active substances for the purpose of biostimulation and catalysis of processes that occur in the rhizosphere under the action of the interconnected functioning of the "plant-microbiome" system.

The action of humic fertilizers on processes through biostimulation of the "plant-microbiome" system depends on the cultivated crop: As a result, depending on the crop, cellulolytic activity increases by 10-14% and microbial biomass by a minimum of 3% (spring peas) and a maximum of 12% (sunflower). As a result, the intensification of the controlled humification process is observed in the upper soil horizon.

In the regeneration of the controlled humification process, two stages are clearly distinguished: a) primary humification (biologically active period April-June) with the formation of humic substances of "young" humic nature and low molecular weight and b) secondary humification with the formation and stabilization of humic substances.

The regeneration of the humification process led to an increase in the humus content in the soil, the optimization and balancing of the nutrient regime (NPK). At the same time, the reduction of pH values determined by the formation of organic acids (malic, citric, acetic) and humic as a result of the controlled humification process is attested.

ACKNOWLEDGEMENTS

This work was supported research subprograms 010801, 010102 funded by the Ministry of Education and Research, Republic of Moldova.

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