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SIGNIFICANCE OF HARVEST RESIDUES IN SUSTAINABLE MANAGEMENT OF ARABLE LAND I. DECOMPOSITION OF HARVEST RESIDUES

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SUMMARY

Harvest residues are parts of cultivated plants that remain on the plot after harvest or grazing. Decomposition of plant residues by microorganisms involves two simultaneous processes: mineralization and humification of carbon compounds. Decomposition processes depend on the type of plant residues, edaphic factors and residue management factors. Edaphic factors dominate in areas exposed to adverse weather conditions, while the type of plant residues largely plays the role of a regulator in favorable environmental conditions. Decomposition of plant residues takes place in two stages; phase I is relatively fast and depends on the initial nitrogen content, and phase II is relatively slow and is determined by the decomposition of lignins and phenols. In general, water-soluble fractions are degraded first, followed by structural polysaccharides, and finally lignin. Low winter temperatures and dry soil during the summer limit microbial decomposition, while microbial decomposition is greatest during the wet warm spring and autumn seasons.

Key words: *plant residues, soil organic matter, soil properties, microbial activity, decomposition*

INTRODUCTION

For the last tens of thousands of years, the dominant role of human beings has been in the exploitation of land in order to increase the production of food, fiber and plant mass for energy production [1]. Ancient writings of the early civilizations of Mesopotamia, Greece and India indicate that there were agro-technical measures to supply the land with nutrients in order to compensate for the nutrients taken out by the yield of cultivated plants, in order to preserve and increase soil fertility [2,3]. Increased production of cash crops in monoculture, with the use of chemical fertilizers and pesticides, has led to a significant increase in grain yield and productivity, but also to a decrease in soil organic matter (SOM), increased soil erosion and contamination of surface and groundwater [4].

Several decades have passed since the beginning of the chemicalization of primary plant production, until agricultural producers have recognized the negative consequences of such land management on the balances of energy and matter exchange and land productivity [5]. In recent years, people's awareness of the importance of soil quality from the ecological aspect [6] and the production of cultivated plants has increased, which has led to renewed interest in harvest residues (HR), green manure and other organic fertilizers as sources of SOM and nutrients for cultivated plants [1]. The aim of this paper is to present literature data on the importance of HR and their decomposition in maintaining the quality of arable land in agriculture.

HR are parts of cultivated plants that are left on the plot after harvest or grazing. This organic matter (OM) was once considered a waste material that requires disposal, but today the prevailing opinion is that these materials are important natural resources, not waste. In all branches of plant production, especially crop and vegetable production, after harvest remains the roots of plants and aboveground HR. This is especially expressed in the production of small grain crops, corn, sunflower, oilseed rape, soybeans and sugar beets, when HR can be a special problem in the next tillage. Annual HR production has reached almost 4 billion tons per year globally [7].

Keeping this large amount of residue on agricultural land can be beneficial due to carbon sequestration. This positive effect can be mitigated if HR retention significantly increases emissions of N_2O, a powerful ozone-depleting greenhouse gas. The amounts of HR in some plant species are as follows: wheat straw 5–7 t ha^{-1}, corn stalks 8–12 t ha^{-1}, sunflower 4–6 t ha^{-1}, soybean 3.5–5 t ha^{-1}, sugar beet 40–60 t ha^{-1}. On non-livestock farms, straw, corn stalks and residues of other plant species remain as by-products, which can be used in several ways: animal feed, raw materials for production of cellulose, paper, plywood, etc., livestock mat, biogas production, raw material for storage of artificial manure and compost and direct involvement in the process of using OM by plowing into the soil.

It is estimated that in the USA, the remains of 19 major cultivated plants amount to 400 million tons per year [8]. The total amount of basic nutrients in plant residues is 40–100 kg $tons^{-1}$, and the content of main nutrients (N + P + K) is 9 million tons per year in the USA and 74 million tons per year in the world [2]. Although large amounts of nutrients are removed from the plot in the grain harvest, significant amounts still remain in vegetative HR (Table 1).

Table 1. Amounts of chemical constituents found in 1 tonne of residues of three cereal straws, maize residues, and pasture herbagea [9]

Elements	Average content (kg t^{-1} of harvest residues)				
	Barley	Oats	Wheat	Pasture	Maize
Nitrogen	4.6	5.9	6.9	21.2	8.4
Phosphorus	0.4	0.6	0.8	2.7	2.0
Potassium	14.3	23,3	13.5	24.6	16.5
Sulfur	1.4	1.1	1.3	2.0	nd*
Calcium	2.6	1.4	1.8	5.6	nd*
Mahnesium	0.8	0.5	0.8	1.4	nd*

nd*- no data

Management of crop residues has important consequences on the total amount of nutrients in the soil, because a significant amount of fertilizer can be saved by returning the produced HR into the soil. In addition, approximately 1.5 billion tonnes of C are stored in world-produced crop residues, which may be an important source of OM added to soil [8].

Plant residues can be used to improve soil health and productivity and are a major source of lignocellulose entering the soil. Lignocellulose can have positive or negative effects on the productivity of cultivated plants, and the challenge and task of producers is to increase the positive value of decomposition of plant residues at the expense of negative value [10,11]. In developing countries, most HRs are used as animal feed, bedding and in industrial use, e.g. such as paper production [10,12,13], and only a small portion of HR is returned to the soil.

DECOMPOSITION OF HARVEST RESIDUES

Degradation of HR represents the microbiologically supported progressive decomposition of organic materials where the end products are carbon (C) and nutrients that are included in the biological circulation in the ecosystem, both locally and globally. HRs decompose very quickly and the C derived from them is only a part of the total C in the soil. It is estimated that about half of global CO_2 production from land comes from the decomposition of annual organic residues. However, there is a huge amount of stable OM in the soil that decomposes very slowly - for centuries [14]. Degradation of plant residues involves two simultaneous and fundamental processes: mineralization and humification of carbon compounds by microorganisms and leaching of soluble compounds down into the soil, where C and nitrogen (N) are progressively mineralized and immobilized. In natural ecosystems, the decomposition of OM is synchronized with the growth of plants and C and other nutrients are used in the system with maximum efficiency [15].

Mineralization of organic nitrogen requires microbial conversion of the organic matter. Part of the converted matter is used for assimilation in microbial tissue and part for oxidation to gain energy (dissimilation). The dissimilation:assimilation ratio (D/A) differs with the type of micro-organisms. The often used term 'organic matter decomposition', refers, to dissimilation. The quantity of decomposed or dissimilated organic matter is thus the difference between the total amount of organic matter that is converted and the amount that is assimilated by the micro-organisms. Similarly, part of the nitrogen that is present in the converted organic material is used in microbial tissue and part is released (mineralized) as inorganic nitrogen. If the converted organic matter is low in nitrogen, the amount of nitrogen that can be converted may be too low to satisfy the assimilation needs of the microbes. In such cases, microbes take inorganic nitrogen from their environment, i.e. the soil solution or the moisture in the organic material.

This process, referred to as immobilization, results in an increase of organic N in the remaining organic material. After some time, the quantity of organic N that is converted is sufficient for the assimilation requirements of the microbes, and then the result of mineralization turns from negative into positive. When the initial C/N ratio of a substrate (C/Ns,i) is higher (lower) than that of the microbes, the fraction of organic N that is mineralized (FMON) is less (higher) than the fraction of organic C that is dissimilated (FDOC), and the C/N ratio of the remaining substrate is decreasing (increasing) during decomposition until it has the same value as that of the microbes (CNm). In case C/Nsi, equals C/Nm, it retains this value, and FMON is equal to FDOC [14,15].

FACTORS CONTROLLING THE DECOMPOSITION OF HARVEST RESIDUES

The processes of decomposition of organic residues are controlled by three main factors: (a) the type of plant residues, (b) edaphic factors and (c) residue management factors [16]. Edaphic factors dominate in areas exposed to adverse weather conditions, while the type of plant residues largely plays the role of a regulator in favorable environmental conditions [17]. Many of these factors are not independent because changing one factor can affect other factors. For example, high soil moisture can lead to lower soil temperature, and aeration and application of surface HR can affect soil moisture and temperature at the same time. Because of these strong interactions, it is often difficult to isolate the effects of specific environmental factors on degradation residues [18].

Plant residues

Plants contain 15-60% cellulose, 10-30% hemicellulose, 5-30% lignin, 2-15% protein and soluble substances such as sugars, amino acids, amino sugars and organic acids, which may contribute up to 10% of dry weight of the plant, as well as other substances in a smaller percentage [19,20,21,22]. The rate of decomposition of OM depends on the relative share of individual fractions, such as soluble sugars, cellulose, hemicellulose and lignin [23]. The half-lives of sugar, hemicellulose, cellulose and lignin are 0.6, 6.7, 14.0 and 364.5 days, respectively, and with the time of decomposition there is a decrease in the quality of the remaining substrate [23]. Decomposition of plant residues takes place in two stages; phase I is relatively fast and depends on the initial N content, and phase II is relatively slow and is determined by the decomposition of lignin and phenol [24].

There are different views regarding the influence of particle size of plant residues on the rate of decomposition of residues and changes in mineralization-immobilization of N in the soil. Small particles can degrade faster than larger ones due to increased surface area and greater dispersion in the soil, increasing susceptibility to microbial attack due to lack of lignified barrier tissue [25], especially if fungi and bacteria do not easily penetrate the residue. Soil fauna plays an important role in increasing the rate of degradation by fragmentation and redistribution of OM, making it more accessible to microbes [26].

The chemical composition of most plants changes significantly during the period of their growth – with age, the content of proteins and ingredients soluble in water is constantly declining, and the amount of hemicellulose, cellulose and lignin increases [27]. In general, water-soluble fractions (sugars, organic acids, proteins, and some structural carbohydrates) are broken down first, followed by structural polysaccharides (cellulose and hemicellulose), and finally lignin. Based on that, the remains of younger plants decompose more easily than the remains of older ones and release more nutrients into the soil [28].

The main task of introducing HR into the soil is to increase the content of SOM and preserve soil fertility, which is why it is necessary to introduce HR with the highest possible content of N and C, i.e. to preserve their content at the time of harvest. It is important to know that drying plant material, even at temperatures below 50-60 °C, significantly increases lignin content due to the production of artifact lignin through a non-enzymatic browning reaction involving N from the plant, resulting in a reduction in mineralized N from HR in relation to fresh plant residues [29].

The content of N in HR varies significantly, while the content of C is about 40-50% in the dry mass, which leads to variations in the C/N ratio in a wide range. The C/N ratio is the mass of carbon to the mass of nitrogen in a particular substance. For example, a C/N ratio of 24:1, means 24 units of carbon to 1 unit of nitrogen. Optimum C/N ratio is 24/1 for desired decomposition of HR. A microorganism living in the soil has a C/N ratio of about 8/1; this is what they must maintain in their bodies. For optimum health the microbe requires approximately 16 parts of carbon for energy and then 8 parts for maintenance.

This is where the ratio of 24/1 comes from [29]. The C/N ratio is important because due to the fact that it has a direct impact on residue decomposition and also nitrogen cycling in soils. Plant residues with high C/N values decompose more slowly than those with lower values and plant residues with high N content show high rates of decomposition and release of nutrients [30]. At C/N ratio values above 20-30%, the decomposition of organic material is significantly reduced. However, the C/N ratio and the N content are not always correlated with the decomposition rate, which is why more complex research on this problem is needed.

Although the content of N and C/N ratio in plant residues are useful in predicting the rate of decomposition of HR, they should be used with some caution, because the C/N ratio does not reveal the availability of C and N to microorganisms. Any factor that increases the rate of decomposition, i.e. the demand for N, leads to an increase in the limit concentration of N (lower limit ratio C/N). This means that a more favorable climate and higher rates of residue change with a larger amount of readily available C in the substrate stimulate higher microbial activity, increase the demand for N and increase the limiting concentration of N [31].

Lignin is very resistant to microbiological degradation, and it is an inhibitor in the process of OM decomposition. Lignin is degraded by small number of microorganisms under aerobic conditions [32]. Increased lignin content in HR reduces the rate of degradation and release of nutrients from plant residues and increases the immobilization of nutrients, especially N. Lignin concentration is a much better predictor of the rate of decomposition of organic matter than N concentration [33].

Polyphenols bind to proteins and other organic nitrogen compounds (amino acids) and form decomposition-resistant complexes [34]. In this way N becomes inaccessible or binds to soluble organic N which is released from the leaves, forming resistant complexes in the soil. Polyphenols also inhibit the action of enzymes [35]. Legumes have the fastest degradation of plant material due to their high protein content and low content of lignin and other inhibitors, such as polyphenolic compounds. It is not possible to predict the decomposition rates of plant residues from individual properties of organic material, such as C/N ratio, lignin content or carbohydrate content, but combining these properties can accurately predict relative decomposition rates of different plant residues [36].

Edaphic factors

Soil acidity (pH) is one of the most important factors influencing the decomposition of plant residues, as it affects both the nature and size of population of microorganisms and the enzymes of microorganisms that degrade OM [37]. In general, HR degradation occurs more rapidly in neutral than in acidic soils. Under field conditions, 42% of the Italian ryegrass (*Lolium multiflorum*) derived C is undegraded after one year in a soil of pH 3.7, and 31% at a pH value of 4.4–6.9 [38]. This may be due to alterations in soil microbial populations and their activities, which occur with changes in soil pH, because with decreasing soil pH there is a decrease in the population of bacteria that decompose plant residues and increase the fungal population.

Soil temperature affects the rate of physiological reactions of organisms and the activity of microbial cells by the laws of thermodynamics, and hence microbial activity and decomposition of HR [39]. Microbial degradation processes are more important than physical and chemical processes in causing HR loss, thus releasing nutrients. The influence of temperature on HR degradation was determined quantitatively as the temperature quotient Q,o' values for the rate of N mineralization in SOM in the temperature range 5–35 °C [40]. Although straw decomposition can occur at 0 °C, the maximum activity of microorganisms, as well as the decomposition of HR, is in the temperature range 20–40 °C [41].

Soil moisture has a great influence on the growth and activity of microorganisms in the soil, which produces significant effects on the decomposition of HR and the circulation of nutrients [42]. The maximum rate of decomposition of plant residues occured at 60% water holding capacity, and the rates decreased at either 30% and 150% of water holding capacity. The rate of straw decomposition as measured by dry weight loss is highest at -0.1 Mpa and decreased as the external soil water potential was lowered [43]. In very dry and very humid soil conditions, the decomposition of OM is inhibited, because the moisture content or aeration of the soil are limiting factors for microbial activity.

Changing the water content in the soil - drying and re-wetting, has a vague effect on the decomposition of plant residues. Although drying stimulates the subsequent mineralization of C and N from humus in the soil, it slows down the mineralization of fresh plant material [44,45]. Drying and wetting of the soil stimulates the turnover of C obtained from the added plant material marked with ^{14}C, and the increase in C is mainly due to the increased turnover of microbial products. The decay rates of ^{14}C biomass are relatively higher due to drying and re-wetting of the soil than the decay rates of ^{14}C that do not originate from biomass. Drying and re-wetting do not affect the degradation of ^{14}C-labeled lignin when incorporated into the soil, but it has been found that the decomposition of added cellulose in the soil increases [46]. Repeated drying and wetting of the soil increases the resistance of certain N compounds of the plant to microbial decomposition. This change in soil moisture can seriously inhibit the growth and/or activity of microbes in the soil.

Aerobic and anaerobic conditions affect the rate of degradation and mineralization – they are slower and less complete in anaerobic than in aerobic conditions [47]. When the soil becomes so moist that larger pores are filled with water, the decomposition of OM is limited by the rate at which oxygen can diffuse to the site of microbial activity, since the oxygen diffusion coefficient in water is 10,000 times slower than in air. Even modest oxygen needs cannot be met if larger pores of the soil are filled with water. The first-order rate constant for rice straw degradation was 0.0054 day^{-1} for phase I (easily degradable fraction) and 0.0013 day^{-1} for phase II (slowly degradable fraction) under aerobic conditions, and the corresponding values for anaerobic conditions were were 0.0024 and 0.0003 day^{-1}, respectively [48].

Available nutrients in the soil, primarily C and N are the primary limiting factor in most soils for microbial growth, although large amounts of C are added to the soil through crop residues. In addition to C, H, O, and N, microorganisms require P, K, S, Mg, Ca, and trace elements [49].

Microorganisms that decompose OM receive the necessary inorganic nutrients (N, P, K, S, Ca, etc.) for growth and development from two sources: (a) those already present in the soil in available plant forms and (b) those that are found in the added organic material itself. N is an element needed in the largest amount to microbes, because it is an integral part of extracellular and intracellular enzymes, nucleic acids and lipoprotein membranes, which makes it the nutrient that most limits the activity of microbes. However, the effects of added N on OM decomposition are variable [50]. Apart from N, other elements also affect decomposition - e.g. Phosphorus increases the rate of decomposition of organic residues, but acts in a strong interaction with N which essentially has a dominant effect [51].

Inorganic natural N in soil enhances OM mineralization [52]. Application of ammonia N in conditions of N deficiency in soil leads to increased microbial respiration, increase in microbial populations and increased mineralization of N [53]. However, a negative or no effect of added N on degradation and microbial activity has also been identified, resulting from: (a) competition between more efficient and weaker decomposers; (b) N blocks the production of certain enzymes and enhances the degradation of more accessible cellulose, where undecomposed lignocellulose accumulates and amino compounds condense with polyphenols; and (c) ammonia toxicity [54]. Nitrogen fertilizer has the potential to affect the decomposition of HR and the mineralization of nitrogen compounds that accumulate in the soil. In soils with low pH values, the mineralization of plant residues is reduced even with the application of N fertilizers. Soils with low pH have reduced nitrification rates, leading to increased NH_4^+ ion concentrations.

The texture, clay content and structure of the soil significantly determine the decomposition rates of HR. Decomposition of plant material is faster in soil with a lower clay content, because clay actually protects OM from decomposition [55]. As the clay content increases, the soil surface also increases, resulting in increased stabilization potential of SOM [56,57]. The role of clay in OM stabilization is more important in warmer soils, where higher decomposition rates can be expected [57,58]. In cold soils, lower temperatures may be a major factor in slowing decomposition and clay content may be less important [59]. Texture also affects the physical properties of the soil [60], which further affects the microbial activity in the soil [34,61]. Soil textures affect the availability of N and P, total OM accumulation, and microbial activity [61]. The soil structure also has a dominant control over the stabilization of SOM, where OM is protected in microaggregates.

Macro and microorganisms of the soil by their activity lead to the decomposition and mineralization of HR, which are mostly biological processes. Abiotic processes are also included here, especially in unfavorable environments, where a significant amount of HR can be lost by abiotic mechanisms, such as fragmentation, physical abrasion, photochemical decomposition, and leaching [16]. Even in conditions when abiotic processes lead to the dominant loss of organic mass, oxidation to CO_2 and other inorganic molecules is mainly the result of the activity of organisms in the soil. Decomposition organisms consist of a complex community of soil biota, including soil microflora and fauna [62]. Fungi and bacteria are ultimately responsible for the biochemical processes of decomposition of organic residues [63]. Soil fauna contributes to the biodegradation and humification of harvest, and in general organic, residues in several ways: (a) fragmentation of organic residues and increasing the area for microbial decomposition, (b) and (c) improving microbial growth and interaction conditions [64]. It is estimated that the direct contribution of soil mesofauna to HR decomposition processes is small, but indirectly important because it affects the survival and functioning of other groups of organisms in the soil [65]. Soil fauna contributes to the decomposition of HR through their fragmentation and improvement of soil structure by creating canals. The role of soil fauna is relatively greater in the degradation of materials with high C/N ratio, and high content of lignin and polyphenols compared to residues with low C/N ratio that are easily degraded by microbes [36]. Termites and ants can be effective in digesting cellulose-containing substances and, in some cases, ligified substances [66].

Conservation tillage and the presence of HR on the soil surface can provide conditions for many decomposing organisms [67]. In principle, more intensive tillage reduces the number of fauna, while reduced tillage is associated with increased decomposition of plant residues [68]. The loss of HR mass is correlated with the moisture content and the number of arthropods in the soil [69]. There is little information in the literature on the combined effects of abiotic and biotic factors on the loss of mass of plant material during the decomposition process.

The community of microbial decomposers is extremely diverse and tolerant of a wide range of environmental and food stresses [69]. The main decomposers of HR, bacteria and fungi, differ in their mode of growth and activity. Bacteria are grouped into colonies that occupy a small volume of soil and their movement in the soil is episodic and associated with soil moisture, root growth, tillage and consumption by soil fauna. Fungi have hyphae that can reach relatively greater distances and penetrate smaller spaces, where they degrade OM by enzyme secretion and transport nutrients back through the hyphae [70]. Microbial activity also depends on substrate temperature. Actinomycetes decompose crop residues mainly at high temperatures, and some species of bacteria and fungi at lower temperatures [71].

Climatic factors

Temperature and precipitation are important factors influencing the decomposition of OM and plant residues [72]. OM losses from soil in humid areas with high temperatures, where OM decays rapidly, are a serious problem. Using a ^{14}C on marked ryegrass, decomposition rates were found to be about four times faster in Nigeria, in the humid tropics, compared to England, with moderate humidity and temperature [73]. Temperature and humidity regimes are good indicators of the microbial C/total C ratio [74]. Low winter temperatures and dry soil during the summer limit microbial degradation, while microbial decomposition is greatest during wet warm spring and autumn seasons [75,76]. At the regional level, the effects of climate on OM degradation are reflected in the accumulation of OM in the soil. Data on SOM from semiarid, semi-humid and humid regions of the world show that soils from warm climates contain less OM compared to colder areas, partly due to faster decomposition of OM [77]

CONCLUSION

In order to preserve the fertility of arable land, its physical, chemical and biological properties must be maintained and improved, which is largely achieved by introducing OM into the soil. HRs are an important natural resource containing OM that is essential for sustainable arable land management.

Proper HR management contributes to increasing OM in soil, binding of greenhouse gases and carbon sequestration. In sustainable land management, the physical, chemical and biological properties of the soil must be maintained in the optimum, because they are a condition for successful microbial decomposition of HR. Where possible, reduced tillage should be carried out as it contributes to greater decomposition of crop residues compared to conservation tillage.

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LITERATURE

[1] Janjić, V., Pržulj, N. (2020). Global natural factors limiting plant production. In: Pržulj N, Trkulja V (eds) From genetics and environment to food. Academy of Sciences and Arts of the Republic of Srpska, Banja Luka, Monograph XLI:1–33.

[2] Kumar, K., Goh, K.M. (2000). Crop Residues and Management Practices: Effects on Soil Quality, Soil Nitrogen Dynamics, Crop Yield, and Nitrogen Recovery. Advances in Agronomy, 68:197–319.

[3] Zakharchenko, E., Tunguz, V. (2020). Effect of ammonium sulfate and phosphogypsum application on nutrients dynamics and acidity of black soil. Bulletin of Sumy National Agrarian University. The Series: Agronomy and Biology, 42(4), 61-69. https://doi.org/10.32845/agrobio.2020.4.8.

[4] Liu, X., Herbert, S.J., Hashemi, A.M., Zhang, X., Ding, G. (2006). Effects of agricultural management on soil organic matter and carbon transformation – a review Plant Soil. Environ., 52(12):531–543.

[5] Roba, T.B. (2018). Review on: The Effect of Mixing Organic and Inorganic Fertilizer on Productivity and Soil Fertility. Open Access Library Journal, 05(06), Article ID:85548, 11 pages. doi.10.4236/oalib.1104618.

[6] Tunguz, V., Petrović, B., Malešević, Z., Petronić, S. (2019). Soil And Radionuclides Of Eastern Herzegovina, Arhiv za tehničke nauke/Archives For Technical Sciences, 1(20):87–92.

[7] Chen , H., Li, X., Hu, F., Shi, W. (2013). Soil nitrous oxide emissions following crop residue addition: a meta analysis. Global Change Biology, 19(10):2956–2964. doi.10.1111/gcb.12274.

[8] Lal, R. (2008). Soils and sustainable agriculture. A review. Agron. Sustain. Dev., 28:57–64. doi.org/10.1051/agro:2007025.
[9] Fraser, P.M., Francis, G.S. (1996). Review of Crop Residue Management in Small Grain Cereals and Maize. A Report for Foundation for Arable Research, Rep. No 312. Crop and Food Res, Lincoln NZ.
[10] Dewi, R.A.S., Indriyati, L.T., Sahari, B., Sabiham, S. (2017). Loss of Soil Organic Matter, Lignocellulose and Microbial Population in Oil Palm Plantations Located at Different Slopes. J. Trop. Soils, 22(3):175–181. ISSN 0852-257X
[11] Chukwuma, O.B., Rafatullah, M., Tajarudin, H.A., Ismail, N. (2021). A Review on Bacterial Contribution to Lignocellulose Breakdown into Useful Bio-Products. Int. J. Environ. Res. Public Health, 18:6001. doi.org/10.3390/ ijerph18116001
[11] Devi, S., Gupta, C., Jat, S.L., Parmar, M.S. (2017). Crop residue recycling for economic and environmental sustainability: The case of India. Open Agriculture, 2:486–494. doi.org/10.1515/opag-2017-0053.
[12] Birla, D., Singh, D., Yadav, B., Kumar, A., Rai, S. (2020). Modern Strategies for Crop Residue Management. Agriculture and Food: E-Newsletter, 2(11)172-175, Article ID: 32558.
[13] Valenzuela, H. (2000). The use of crop residues on the farm. CTAHR Hanai Ai Sustainable Agriculture News letter. Univ Hawaii Coop Extension Service. Winter 2020.
[14] Hoffland, E., Kuyper, T.W., Coman T. (2020) Eco-functionality of organic matter in soils. Plant Soil., 455:1–22. doi.org/10.1007/s11104-020-04651-9.
[15] Merkle, F.G. (2017). The decomposition of organic matter in soils. Masters Theses, Available at: https://scholarworks.umass.edu/theses/1235, Accessed: 14. November 2021.
[16] Grzyb, A., Wolna-Maruwka, A., Niewiadomska, A. (2020). Environmental Factors Affecting the Mineralization of Crop Residues. Agronomy, 10(12):1951. doi.org/10.3390/agronomy10121951.
[17] Dindaroglu, T., Tunguz, V., Babur, E., Menshov, O., Battaglia, M.L. (2021). Determination of the relationship among compound Topographic Index (CTI), soil properties and land-use in karst ecosystems, Physical Geography. Available at: https://www.tandfonline.com/doi/abs/10.1080/02723646.2021.1961361?src=&journalCode=tphy20, pp 1–23. Accessed: 25 October 2021.
[18] Fruit, L., Recous, S., Richard, G. (1999). Plant Residue Decomposition: Effect of Soil Porosity and Particle Size. In: Berthelin J, Huang PM, Bollag JM, Andreux F (eds) Effect of Mineral-Organic-Microorganism Interactions on Soil and Freshwater Environments. Springer, Boston, MA. doi.org/10.1007/978-1-4615-4683-2_20.
[19] Paul, E.A., Clark, F.E. (1989). Soil Microbiology and Biochemistry. Academic Press, Orlando, FL
[20] Pržulj, N., Momčilović, V. (2001a). Genetic variation for dry matter and nitrogen accumulation and translocation in two-rowed spring barley. I. Dry matter translocation. European Journal of Agronomy, 15:41–254.
[21] Pržulj, N., Momčilović, V. (2001b). Genetic variation for dry matter and nitrogen accumulation and translocation in two-rowed spring barley. II. Nitrogen translocation. European Journal of Agronomy, 15:255–265
[22] Pržulj, N., Momčilović, V. (2003). Dry matter and nitrogen accumulation and use in spring barley. Plant, Soil and Environment, 49(1):36–47.
[23] Kothawala, D.N., Kellerman, A.M., Catalán, N., Tranvik, L.J. (2020). Organic Matter Degradation across Ecosystem Boundaries: The Need for a Unified Conceptualization. Trends in Ecology and Evolution, 36(2). doi.org/10.1016/j.tree.2020.10.006. Available at: https://www.cell.com/trends/ecology-evolution/fulltext/S0169-5347(20)30283-4. Accessed: 16 September 2021.
[24] Janzen, H.H., Kucey, R.M.N. (1988). C,N, and S mineralization of crop residues as influenced by crop species and nutrient regime. Plant Soil, 106:35–41.
[25] Rasse, D.P., Dignac, M.F., Bahri, H., Rumpel, C., Mariotti, A., Chenu, C. (2006) Lignin turnover in an agricultural field: from plant residues to soil-protected fractions. European Journal of Soil Science, 57(4):530–538.
[26] Gatiboni, L.C., Coimbra, J.L.M., Denardin, R.B.N., Wildner, L.P. (2011). Microbial biomass and soil fauna during the decomposition of cover crops in no-tillage system. Rev. Bras. Ciênc. Solo., 35(4):1051–1057.
[27] Kiskini, A., Vissers, A., Vincken, J.P., Gruppen, H., Wierenga, P.A. (2016). Effect of Plant Age on the Quantity and Quality of Proteins Extracted from Sugar Beet (Beta vulgaris L.) Leaves. J. Agric. Food Chem., 9(64):8305–8314.
[28] Baitsaid, A., Schaffer, B., Vargas, A.I., Li, Y., Liu, G.D. (2018). Effect of plant age on in-soil decomposition and nitrogen content of sunn hemp tissue. Communications in Soil Science and Plant Analysis, 49(21):2680–2688. doi.10.1080/00103624.2018.1526954.
[29] Moore, J.C., Walter, D.E., Hunt, H.W. (1988). Arthopod regulation of micro- and meso biota in below-ground detrital food webs. Annu. Rev. Entomo., 33:419–439.
[30] Nicolardot, B., Recous, S., Mary, B. (2001). Simulation of C and N mineralisation during crop residue decomposition: A simple dynamic model based on the C:N ratio of the residues. Plant and Soil, 228(1):83–103. doi.10.1023/A:1004813801728.

[31] Dendooven, L., Verstraeten, L., Vlassak, K. (1990). The N-mineralization potential: An undefinable parameter. In: Merckx, R., Vereecken, H., Vlassak, K. (eds) Fenilization and the Environment, pp 170‒181. Leuven Universiry Press, Belgium.
[32] Khan, M.U., Ahring, B.K. (2019). Lignin degradation under anaerobic digestion: Influence of lignin modifications -A review. Biomass and Bioenergy, 128:105325.
[33] Talbot, J.M., Treseder, K.K. (2012). Interactions among lignin, cellulose, and nitrogen drive litterchemistry–decay relationships. Ecology, 93(2):345–354.
[34] Chen, B., Liu, E., Tian, Q., Yan, C., Zhang, Y. (2014). Soil nitrogen dynamics and crop residues. A review. Agronomy for Sustainable Development, Springer Verlag/EDP Sciences/INRA, 34(2):429–442. ff10.1007/s13593-014-0207-8ff. ffhal-01234828f. Available at: https://hal.archives-ouvertes.fr/hal-01234828/document. Accessed: 16 November 2021.
[35] Rohn, S., Rawel, H.M., Kroll, J. (2002). Inhibitory Effects of Plant Phenols on the Activity of Selected Enzymes. J. Agric. Food Chem., 50(12):3566–3571.
[36] Tian, G., Brussaard, L., Kang, B.T. (1995). An index for assessing the quality of plant residues and evaluating their effects on soil and crop in the (sub-) humid tropics. Appl. Soil Ecol., 2:25–32.
[37] Xu, J.M., Tang, C., Chen, Z.L. (2006). Chemical composition controls residue decomposition in soils differing in initial pH. Soil Biology and Biochemistry, 38(3):544–552.
[38] Jenkinson, D.S. (1977). Studies on the decomposition of plant material in soil. V. The effects of plant cover and soil type on the loss of carbon from 14C labelled ryegrass decomposing under field conditions. J. Soil. Sci. 28:424–434.
[39] Wallenstein. M., Allison, S.D., Ernakovich, J., Steinweg, J.M., Sinsabaugh, R. (2010). Controls on the Temperature Sensitivity of Soil Enzymes: A Key Driver of In Situ Enzyme Activity Rates. In: Shukla, G., Varma, A. (eds) Soil Enzymology. Soil Biology 22. Springer, Berlin, Heidelberg. doi.org/10.1007/978-3-642-14225-3_13.
[40] Cabrera, M.L., Kissel, D.E., Vigil, M.F. (2005). Nitrogen Mineralization from Organic Residues. Journal of Environmental Quality, 34(1):75‒79.
[41] Vimal, S.R., Singh, J.S., Arora, N.K., Singh, S. (2017). Soil-Plant-Microbe Interactions in Stressed Agriculture Management: A Review. Pedosphere, 27(2):177‒192.
[42] Zhu, Y.Z., Li, Y.Y., Han, J.G., Yao, H.Y. (2019). Effects of changes in water status on soil microbes and their response mechanism: A review. The Journal of Applied Ecology, 30(12):4323‒4332. doi.10.13287/j.1001-9332.201912.031
[43] Summerell, B.A., Burgess, L.W. (1989). Decomposition and chemical composition of cereal straw. Soil BioL Biocliem, 21:551‒559.
[44] Coppens, F., Garnier P., Gryzem, D., Merckx, R., Recous, S. (2006). Soil moisture, carbon and nitrogen dynamics following incorporation and surface application of labelled crop residues in soil columns. European Journal of Soil Science, 57:894–905. doi.10.1111/j.1365-2389.2006.00783.x.
[45] Jovović, M., Tunguz, V., Mirosavljević, M., Pržulj, N. (2018). Effect Of Salinity And Drought Stress On Germination And Early Seedlings Growth Of Bread Wheat (Triticum aestivum L.). Genetika, 50(1):285–298. doi.10.2298/GENSR1801285J
[46] Chen, X., Hu, Y., Feng, S., Yichao, R. (2018). Lignin and cellulose dynamics with straw incorporation in two contrasting cropping soils. Sci. Rep., 8:1633. doi.org/10.1038/s41598-018-20134-5.
[47] Olk, D.C., Samson, M.I., Gapas, P. (2007). Inhibition of nitrogen mineralization in young humic fractions by anaerobic decomposition of rice crop residues. European Journal of Soil Science, 58(1):270–281.
[48] Reddy, K.R., Khallel, R., Overcash, M.R. (1980). Carbon transformations in the land areas receiving organic wates in relation to nonpoint source pollution: A conceptual model. J. Environ. Qual. 9:434–442.
[49] Miransari, M. (2013). Soil microbes and the availability of soil nutrients. Acta Physiol. Plant. 35:3075–3084. doi.org/10.1007/s11738-013-1338-2.
[50] Jenkinson, D.S. (1981). The fate of plant and animal residues in soil. In: Greenland, D.A., Hayes, M.H.B. (eds) The Chemistry of Soil Processes, pp 505‒561, Wiley, Chichester.
[51] Cheshire, M.V., Chapman, S.J. (1996). Influence of the N and P status of plant material and of added Nand P on the mineralization from 14C-labelled ryegrass in soil. BioL Fertil Soils, 21:166‒170.
[52] Painter, H.A. (2013). Microbial transformations of inorganic nitrogen. In: Jenkins, S.H. (ed) Proceedings of the Conference on Nitrogen As a Water Pollutant, Pergamon, 8(4):3‒29. doi.org/10.1016/B978-1-4832-1344-6.50003-4.
[53] Wang, J., Bao, J., Su, J., Li, X., Chen, G., Ma, X. (2015). Impact of inorganic nitrogen additions on microbes in biological soil crusts. Soil Biology and Biochemistry, 88:303–313. doi.org/10.1016/j.soilbio.2015.06.004
[54] Hobbie, S.E. (2005). Nitrogen effects on decomposition: a five-year experiment in eight temperate sites. Ecology, 89(9):2633–2644. doi.org/10.1890/07-1119.1.
[55] Toleikiene, M., Arlauskiene, A., Fliesbach, A., Iqbal, R., Sarunaite, L., Kadziuliene, Z. (2020). The decomposition of standardised organic materials in loam and clay loam arable soils during a non-vegetation period. Soil & Water Res., 15:181–190. doi.org/10.17221/31/2019-SWR.

[56] Castellano, M.J., Mueller, K.E., Olk, D.C., Sawyer, J.E., Six, J. (2015). Integrating plant litter quality, soil organic matter stabilization, and the carbon saturation concept. Global Change Biology, 21(9):3200–3209. doi.org/10.1111/gcb.12982.

[57] Li, H., Santos, F., Butler, K., Herndon, E. (2021). A Critical Review on the Multiple Roles of Manganese in Stabilizing and Destabilizing Soil Organic Matter. Environ. Sci. Technol., 55(18):12136–12152.

[58] Tvica, M., Čivić, H., Tunguz, V. (2020). The influence of changes in way of use, in climate and in hydrological conditions on Histosol in reclamation area in peatland Ždralovac, subtitle: Possibilities of re-establish of agricultural production in abandoned reclamation area in peatland Ždralovac in Livanjsko polje after 25 yr., 30th International Scientific-Experts Congress on Agriculture and Food Industry – Sarajevo 2019. IFMBE Proceedings, pp 25–35. ISBN 978-3-030-40048-4 ISBN 978-3-030-40049-1 (eBook), Available at: https://link.springer.com/chapter/10.1007/978-3-030-40049-1_3. Accessed: 11 September 2021.

[59] Onwuka, B.M. (2016). Effects of Soil Temperature on Some Soil Properties and Plant Growth. Scholarly Journal of Agricultural Sciences, 6(3):89–93.

[60] Dexter, A.R. (2004). Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma, 120(3-4):201–214.

[61] Hamarashid, N.H., Othman, M.O., Hussain, M.-A.H. (2010). Effects of soil texture on chemical compositions, microbial populations and carbon mineralization in soil. Egypt. J. Exp. Biol. (Bot) 6(1):59–64.

[62] Petrović, B., Đurić, S., Vasić, M., Tunguz, V., Pokluda, R. (2018). Effect of Bean Cultivars on Soil Microorganisms. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 66(1):0155–0160. doi. 10.11118/actaun201866010155.

[63] Preusser, S., Poll, C., Marhan, S., Angst, G., Mueller, C.W., Bachmann, J., Kandeler, E. (2019). Fungi and bacteria respond differently to changing environmental conditions within a soil profile. Soil Biology and Biochemistry 137:107543.

[64] Guggenberger, G. (2005). Humification and Mineralization in Soils. In: Varma, A., Buscot, F. (eds) Microorganisms in Soils: Roles in Genesis and Functions. Soil Biology, 3. Springer, Berlin, Heidelberg. doi.org/10.1007/3-540-26609-7_4.

[65] Beare, M.H. (1997). Fungal and bacterial pathways of organic matter decomposition and nitrogen mineralisation in a arable soils. In: (Brussard, L., Cerrato R.F. (eds) Soil Ecology in Sustainable Agricultural Ecosystems, pp 37–70. CRC Press, Boca Raton, FL.

[66] Bruyn, L.A.L., Conacher, A.J. (1990). The role of termites and ants in soil modification – a review. Australian Journal of Soil Research, 28(1):55–93.

[67] Stockfisch, N., Forstreuter, T., Ehlers, W. (1999). Ploughing effects on soil organic matter after twenty years of conservation tillage in Lower Saxony, Germany. Soil and Tillage Research, 52(1–2):91–101.

[68] Tebrügge, F., Düring, R.-A. (1999). Reducing tillage intensity — a review of results from a long-term study in Germany. Soil and Tillage Research, 53(1):15–28.

[69] Reddy, M.V., Reddy, V.R., Yule, D.E., Cogle, A.L., George, P.J. (1994). Decomposition of straw in relation to tillage, moisture, and arthropod abundance in a semi-arid Alfisol. Bioi. Ferril Soils 17:45–50.

[70] Frey, S.D. (2019). Mycorrhizal Fungi as Mediators of Soil Organic Matter Dynamics. Annual Review of Ecology, Evolution, and Systematics, 50:237–259. doi.org/10.1146/annurev-ecolsys-110617-062331.

[71] Muhammad, I., Wang, J., Sainju, U.M., Zhang, S., Zhao, F., Khan, A. (2021). Cover cropping enhances soil microbial biomass and affects microbial community structure: A meta-analysis. Geoderma, 381:114696.

[72] Moinet, G.Y.K., Hunt, J.E., Kirschbaum, M.U.F., Morcom, C.P., Midwood, A.J., Millard, P. (2018), The temperature sensitivity of soil organic matter decomposition is constrained by microbial access to substrates. Soil Biology and Biochemistry, 16:333–339. doi.org/10.1016/j.soilbio.2017.10.031.

[73] Barnard, G., Kristoferson, L. (1985). Agricultural Residues as Fuel in the Third World, Tech. Rep. 4. International Institute for Environment and Development, Earthscan, London.

[74] Quemada, M. (2005). Predicting crop residue decomposition using moisture adjusted time scales. Nutrient Cycling in Agroecosystems, 70:283–291.

[75] Van Vliet, P., Vadakattu, G., Abbott, L.K. (2000), Soil biota and crop residue decomposition during summer and autumn in south-western Australia. Applied Soil Ecology, 14(2):111–124. doi.10.1016/S0929-1393(00)00046-9

[76] Forbes, S.L., Perrault, K.A., Stefanuto, P.H., Nizio, K.D., Focant, J-F. (2014). Comparison of the Decomposition VOC Profile during Winter and Summer in a Moist, Mid-Latitude (Cfb) Climate. PLoS One 9(11):e113681. doi.10.1371/journal.pone.0113681.

[77] Luan, J., Liu, S., Chang, S.X., Wang, J., Zhu, X., Liu, K., Wu, J. (2014). Different effects of warming and cooling on the decomposition of soil organic matter in warm–temperate oak forests: a reciprocal translocation experiment. Biogeochemistry, 121:551–564. doi.org/10.1007/s10533-014-0022-y.