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Resource-Saving Measures to Improve Soil Fertility and Increase Plant Productivity Through the Use of Straw

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ABSTRACT

Highly productive soils in Ukraine have been losing their main quality indicators in the last decade. This is due to the violation of basic agricultural laws, particularly in the selection of agricultural crops in crop rotation, climate change, and other negative manifestations. Successful farming in the South Steppe zone of Ukraine significantly depends on moisture conditions, specifically the amount of precipitation during plant vegetation and initial moisture reserves during sowing. The first limiting factor for crop yields in arid regions is moisture. Depleted and compacted soils are unable to accumulate and retain it. Under such conditions, it is necessary to develop new approaches and implement the previously developed technological measures that would contribute to increasing the productivity of agricultural crops while preserving soil fertility. This involves enriching soils with organic matter, which structures them as well as increases their water absorption and retention capacity. In the absence of manure in the fields, it is advisable to use post-harvest residues of all crops and straw. These are the most resource-efficient and environmentally friendly measures. It has been determined that incorporating straw into the soil can increase the yield and quality of agricultural crops, as demonstrated in the cultivation of sorghum.

Keywords: soil fertility, use of straw as organic fertilizer, humus content, soil treatment measures, bio-preparations, sorghum, crop yield, product quality.

INTRODUCTION

The main foundation on which agriculture is based is soil. Its fertility directly determines the success and level of crop yield of agricultural crops. Ukrainian soils are considered some of the best in the world in terms of their genetic potential. However, in recent years, the main components that determine soil fertility have unfortunately decreased. This is manifested in the reduction of humus content, organic matter, basic macro- and microelements, deterioration of its structure, water-physical properties, etc. [Balyuk S.A. et al., 2017; Medvedev V.V. et al., 2018; Skrylnyk Y.V. et al., 2018].

The gradual loss of the main indicators of soil fertility, as determined by many studies including authors' own, is closely related to the deviations from technological measures for growing plants that violate the basic laws of agriculture. This is primarily due to the disruption of scientifically recommended crop rotation, including unjustified increase in sunflower cultivation while reducing the share of leguminous crops and perennial grasses in the crop structure [Gamayunova V.V. et al., 2018.].

This situation is also related to the stable increase in production volumes, intensification of the agricultural sector during the period of independence of Ukraine, significant changes in crop structure, climatic conditions, and soil fertility. In the near future, an increase in crop production is expected after the post-war period. Unfortunately, almost no one analyzes the increase in production regarding its impact on soil fertility and anthropogenic load on them. In addition, the volumes of produced products do not always compensate for the removal of nutrients by applying a sufficient amount of fertilizers, especially organic ones [Veremeyenko S.I. and Semenko L.O., 2019].

According to the State Statistics Service of Ukraine, in 1990, 141 kg of mineral fertilizers were applied per 1 ha (including 59 kg of nitrogen, 43 kg of phosphorus, and 39 kg of potassium), while in 2018, the amount decreased to 112 kg per 1 ha (79 kg of nitrogen, 16 kg of phosphorus, and 17 kg of potassium). These reduced doses of essential nutrients lead to a negative balance and further deterioration of soil fertility and gradual depletion of the NPK content. The situation is even worse with the use of organic fertilizers. If in 1990, 8.6 tons per 1 ha were applied, by 2018, this rate had decreased to 0.5 tons per 1 ha, or by 17 times. The highest crop yields are achieved with optimal use of organic-mineral nutrition systems [Gamayunova V. and Sydiakina O., 2023; Vasilenko M.H., 2017; Hospodarenko H. M. et al., 2019]. Unbalanced application of fertilizers with a disruption of the ratio under conditions of intensive agriculture poses a threat of soil degradation. Under the conditions of high land plowing and intensive land use without balanced management, soil degradation becomes a major problem for agricultural lands not only in Ukraine but also worldwide [Medvedev V.V. et al., 2018; Veremeenko S.I. and Furmants O.A., 2014].

In the absence of semi-rotten manure due to a significant decrease in livestock, rising prices of mineral fertilizers, and weakened economic viability of farms, the concern for preserving and restoring soil fertility must be based on resource-saving principles. To enrich the soil with organic matter, post-harvest and root residues of all agricultural crops are used, if possible, by sowing cover crops with leguminous components and herbs that enrich the soil with fresh organic matter and biological nitrogen [Olifirovych V.O. et al., 2018; Karbivska U. et al., 2020; Tkachuk O.P. and Ovcharuk V.V. 2020].

The most cost-effective way to enrich the soil with organic matter is by incorporating straw. Its effectiveness as an organic fertilizer has been established for improving soil structure, water-physical properties, and increasing crop yields, especially in the years following its decomposition. Numerous studies have shown that straw fertilization increases humus content, organic matter, water-stable aggregates, etc. [Ovcharuk V.V., 2020].

Depending on the duration of the vegetation of crops and the timing of sowing the next crop, post-harvest and intermediate green manure (cover crop) plantings are introduced, which are a powerful source of enriching the soil with fresh organic matter, humus, NPK, and micronutrients. Any plants that are capable of accumulating significant aboveground biomass in a short period of vegetation can be used for this purpose. It is most effective to grow mixtures with a leguminous component, so that the soil will be replenished with free biological nitrogen as well [Ovcharuk V.V., 2020a; Ovcharuk V., 2020b; According to the information from the Kherson branch of the State Soil Protection Department, 2019]. This organic matter is capable of rapid decomposition, as it contains enough moisture, nitrogen compounds, and does not require additional moisture for swelling or the application of nitrogen fertilizer. It is advisable to combine cover crops with straw. Such a combination has a complex effect on improving the physical, chemical, biological, and other positive effects on soil fertility [Sendetsky V.M., 2019; Gamajunova V. et al., 2021; Popov S. et al., 2022].

More humus is formed from the incorporation of straw into the soil. This is because it is known to contain over 80% dry organic cellulose material and is practically devoid of moisture. Each ton of straw, by its organic content, is able to replace 4–5 tons of semi-rotted manure, positively affecting the quantity and quality of humus formation. Newly formed humic substances are characterized by adhesive properties and have the greatest impact on creating an agronomically valuable, bound, water-resistant structure. Without the participation of humic substances, the soil structure will not be characterized by water resistance, as this property is provided by organic colloids, primarily calcium humates.

In addition to organic matter, straw contains up to 0.35% nitrogen, 0.15% phosphorus, 1.7% potassium, and all necessary plant microelements. Under irrigated conditions and with sufficient soil moisture, straw decomposes quickly, within a year. Burning straw is an unacceptable practice. This not only burns fresh organic matter but also burns the humus of the topsoil that has been formed over the years. In addition, the ash left instead of straw does not provide soil structure and humus growth; on the contrary, the quality of humus deteriorates when straw is burned; the content of fulvic acid in its composition increases, and the content of humic acid decreases [Ovcharuk V.V., 2020a].

Thus, straw is the cheapest organic fertilizer, and it should not be removed from the field but immediately incorporated into the soil. It can replace the lack of manure [Popov S. and Avramenko S., Manko K., 2022.]. Moreover, in recent years, there have been biodegraders and biopreparations available that accelerate its decomposition [Ivanchuk M.D., 2022.; Sydyakina O.V., 2021; Gamajunova V. et al., 2021.].

Straw, more than other organic fertilizers, contains organic matter, in particular, cellulose, hemicellulose and lignin, which are carbohydrate energy substrates for soil microorganisms.

The yield of all agricultural crops reaches maximum levels with the combined use of organic and mineral fertilizers. Under such conditions, even increased doses of nitrogen fertilizer will not negatively affect the quality of products, because a certain part of nitrogen will be temporarily fixed by microorganisms that decompose fresh organic matter. The nitrogen assimilated by microbiota will be fixed by them for a certain period and will not be «harmful». Conversely, it acquires the properties of biological nitrogen, is not lost or washed out of the soil, but becomes available to plants only after the death of microorganisms. Thus, the soil microbiota will be an important feature in influencing the preservation and improvement of both the nitrogen balance as well as the purification of soils from various pollutants.

The maximum effect from using straw as a fertilizer can be achieved not only by applying the necessary doses of nitrogen fertilizers but also by treating it with a straw destructor. Unlike traditional technology (burning or plowing under crop residues), a straw destructor accelerates the decomposition of plant residues without destroying valuable fresh organic matter, improves soil fertility, increases crop productivity by 10-30%, as well as prevents the development of pathogenic microorganisms and pests in the soil [Gamajunova V. et al., 2021].

It is important to choose the right soil cultivation technology and calculate the effectiveness of distributing crop residues: for incorporation and in the upper soil layer as surface mulch cover. It is advisable to apply a specific technology in each region and on each specific field [Kyryliuk V.P., 2018.].

RESEARCH METHODOLOGY

Taking into account the importance, positive influence of straw on the main indicators of soil fertility and plant productivity, as well as the presence of biopreparations and straw destructors, field research was conducted. During 2019–2021, after harvesting winter wheat, straw was incorporated into the soil, and the following year in the spring, sorghum was sown.

The research was conducted on chernozem soil in the southern region at the Educational and Scientific Practical Center of Mykolayiv National Agrarian University. Straw in the amount of 6 t/ha was placed at different depths and distributed in different layers of the soil (factor A):

- Control – shelf plowing to a depth of 25–27 cm (traditional technology).
- Conservation technology – carrying out chisel tillage of the soil to a depth of 25–27 cm.
- Mulching technology – discing to a depth of 12–14 cm.

In early spring, harrowing was performed in two passes with heavy harrows, and pre-sowing cultivation to a depth of 5-6 cm was carried out. Straw was plowed into the soil to the indicated depth of tillage in relation to factor A (factor B): A – control (without straw plowing); B – straw + Biocomplex BTU-r; C – straw + EcoStern; D – straw + BTU-r + Eco Stern.

The study involved the cultivation of a mid-ripening hybrid of sweet sorghum Mamont. In the years of the study, sowing was carried out at optimal times in well-heated soil (12–14 °C at a depth of 10 cm) using wide-row (70 cm) sowing with a seeding rate of 130 thousand seeds per hectare. The area of the sowing area is 120 m^2, the accounting area is 50 m^2, the experiment is repeated four times. The mass of sugar sorghum in the phase of milky-waxy grain maturity was collected with a combine harvester from the entire accounting area of the plot, with subsequent determination of yield. The area of the leaf surface was determined by means of the cutting method, and the content of total sugars was determined using a refractometer.

All research, observations, measurements, and agronomic practices were carried out in accordance with zonal methodological recommendations, state standards, and research methods [Ushkarenko V.O et al., 2014; Vozhegova R.A. et al., 2014]. Agrostat new software was used to determine correlation-regression dependencies [Ushkarenko V.O et al., 2013].

RESEARCH RESULTS AND THEIR JUSTIFICATION

In the years of the study, sorghum seedlings emerged on the 7th–10th day after sowing (beginning of the third decade of May), the phase of forming 4–5 leaves occurred 17–20 days after emergence, the tillering phase occurred 21–23 days later, and heading occurred at the beginning of July, 35–38 days after sowing, depending on the research variant.

The duration of the vegetative period of sorghum plants mainly varied depending on the variant of using straw as organic fertilizer and to a lesser extent on the adopted cultivation technology – method and depth of soil tillage (Table 1).

Thus, the shortest vegetative period (116 days) was determined in the control variant without straw incorporation using mulching cultivation technology (discing to a depth of 12–14 cm). The longest vegetative period (124 days) was observed with traditional cultivation technology incorporating straw into the soil combined with inoculation with the bacterial preparation Biocomplex-BTU-r and the straw destructor EcoStern. At the same time, the average duration of the vegetative period with traditional technology (plowing to a depth of 25–27 cm) was 121 days. The use of conservation tillage technology (chiseling to a depth of 25–27 cm) did not affect this indicator, and with mulching technology (discing to a depth of 12–14 cm), the vegetative period decreased on average by 2 days.

For all the cultivation technologies studied, a close relationship was observed between the duration of the vegetative period of sweet sorghum plants and the yield of green mass. The determination coefficient R^2 varied depending on the variant in the range from 0.981 to 0.995. The determination of the correlation between the methods of earning straw and the yield of green mass also indicated a fairly close connection – the determination coefficient R_2 for all variants ranged from 0.835 to 0.994. Moreover, a closer relationship was established in all variants using straw.

The investigated factors influenced the biometric indicators of sweet sorghum plants, particularly their height (Table 2).

The tallest plants (265.8 cm) were formed in the variant of combined inoculation of straw with the bacterial preparation Biocomplex-BTU-r and the stover destructor EcoStern. The shortest height (219.9 cm) was characteristic of plants grown using mulching technology without earning straw. On average, the implementation of conservation and mulching cultivation technologies

Table 1. The duration of the vegetation period of sugar sorghum hybrids depends on the studied factors in the phase of grain wax ripeness, days (average for 2020–2022)

No	Soil treatment technology (factor A)	Method of using straw* (factor B)				Average for factor A
		A	B	C	D	
1.	Traditional (control)	117	120	122	124	121
2.	Conservative	118	120	121	123	121
3.	Mulching	116	118	120	121	119
Average for factor B		117	119	121	123	

Note: A – control without straw; B – straw + Biocomplex-BTU-r; C – straw + EcoStern; D – straw + Biocomplex-BTU-r + EcoStern.

Table 2. The height of sugar sorghum plants in the milky ripeness phase of the grain depends on the studied factors (average for 2020–2022), cm

No	Soil treatment technology (factor A)	Method of using straw* (factor B)				Average for factor A
		A	B	C	D	
1.	Traditional (control)	231.3	244.2	255.6	265.8	249.2
2.	Conservative	227.8	243.7	254.9	263.1	247.4
3.	Mulching	219.9	233.8	243.1	254.0	237.7
Average for factor B		226.3	240.6	251.2	261.0	244.8

Note: A – control without straw; B – straw + Biocomplex-BTU-r; C – straw + EcoStern; D – straw + Biocomplex-BTU-r + EcoStern.

contributed to the formation of shorter plants compared to the control by 1.8 cm and 11.5 cm, respectively.

Earning straw led to an increase in the height of sweet sorghum plants. Inoculation of straw with the Biocomplex-BTU-r biopreparation increased it by 14.3 cm compared to the control, the EcoStern destructor – by 24.9 cm, and the combination for processing Biocomplex-BTU-r and EcoStern – by 34.7 cm.

Regardless of the adopted cultivation technology of sweet sorghum, a close relationship was observed between the plant height indicators and the yield of green mass: the determination coefficient was determined within the range from 0.985 to 0.997 (a strong degree of connection).

Crops with an assimilation surface area of plants reaching 40–50 thousand m²/ha quickly and leaves remaining green for longer are considered the most productive. The maximum value (54.1 thousand m²/ha) of the leaf surface area of sweet sorghum, depending on the investigated factors, was determined in the phase of milky-waxy ripeness of grain in the plowing variant with straw treatment combined with the Biocomplex-BTU-r preparation and the EcoStern stubble destructor (Table 3). The minimum leaf area (34.5 thousand m²/ha) for the years of research was formed using mulching (surface tillage by 12–14 cm) without earning straw. On average, conservation and mulching cultivation technologies of sweet sorghum resulted in a certain decrease in the assimilation surface area of plants by 0.6 and 3.7 thousand m²/ha, respectively, compared to plowing.

The cultivation of sweet sorghum hybrid using straw led to an increase in the leaf surface area of the crop. In the control variant without earning straw, it averaged 36.2 thousand m²/ha. Processing the straw with Biocomplex-BTU-r increased it by 6.3 thousand m²/ha, with EcoStern by 11.2 thousand m²/ha, and with the combination of both preparations by 15.2 thousand m²/ha.

For all cultivation technologies, a close relationship was observed between the leaf area in the milky-waxy ripeness phase of the grain and the yield of green mass of sorghum. The determination coefficient (R_2) ranged from 0.987 to 0.998, indicating a very strong statistical connection according to Chedoke's scale.

A strong degree of statistical connections between the leaf surface area and the yield of green mass was also determined for different methods of straw treatment in the soil. The determination coefficient ranged from 0.958 (in the control) to 0.989–0.995 (for straw inoculation).

Research on drought-resistant sweet sorghum crops has identified the importance of the plant's leaf surface area in their ability to more effectively use moisture for crop production while reducing evaporation losses, thus preventing unproductive water loss [Gamayunova V. et al., 2023]. This is particularly important for the conditions of the Southern Steppe of Ukraine, where moisture reserves are a limiting factor in crop yield formation.

The use of straw and other organic fertilizers improves soil water retention capacity, as it has already been mentioned. It was found that the yield of green biomass of sweet sorghum in the milky-waxy ripeness phase varied significantly depending on the investigated factors and the year of cultivation (Figure 1).

Regarding the method of soil cultivation, the maximum productivity (71.4 t/ha) of the sweet sorghum hybrid was achieved using the traditional cultivation technology with the processing of straw with Biocomplex-BTU-r and EcoStern (Figure 2). The minimum yield (55.7 t/ha) was observed for the mulching technology (surface soil treatment) and cultivation of sorghum without straw incorporation. On average, the amount of green biomass in the variant without straw incorporation was 57.1 t/ha, which is 5.7 t/ha less than with the addition of Biocomplex-BTU-r, and

Table 3. The area of the leaf surface of the sowing of sugar sorghum plants in the phase of milky-waxy maturity of the grain, depending on the studied factors, thousand m²/ha (average for 2020–2022)

No	Soil treatment technology (factor A)	Method of using straw* (factor B)				Average for factor A
		A	B	C	D	
1.	Traditional (control)	37.5	43.9	48.8	54,1	46.1
2.	Conservative	36.7	43.7	48.1	53,5	45.5
3.	Mulching	34.5	39.9	45.4	49,6	42.4
Average for factor B		36.2	42.5	47.4	52,4	44.6

Note: A – control without straw; B – straw + Biocomplex-BTU-r; C – straw + EcoStern; D – straw + Biocomplex-BTU-r + EcoStern.

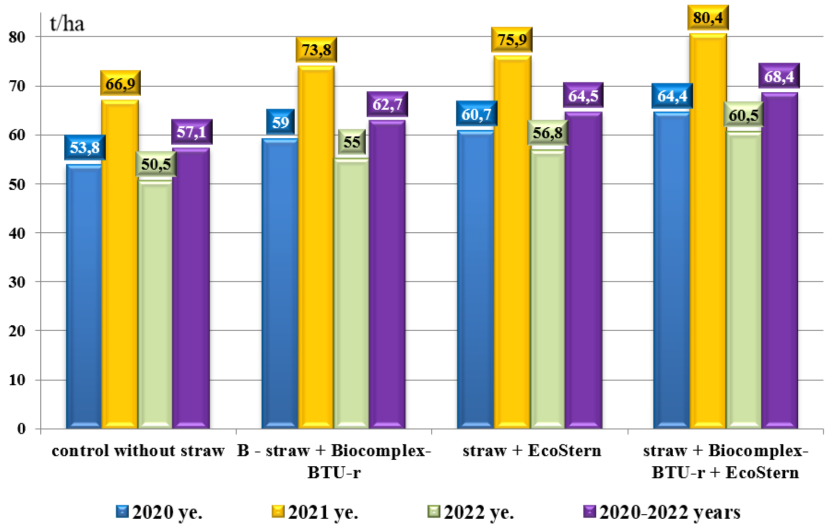

Figure 1. The yield of the green mass of the sugar sorghum in the phase of milk-wax maturity of the grain depending on the studied factors in the years of cultivation, t/ha

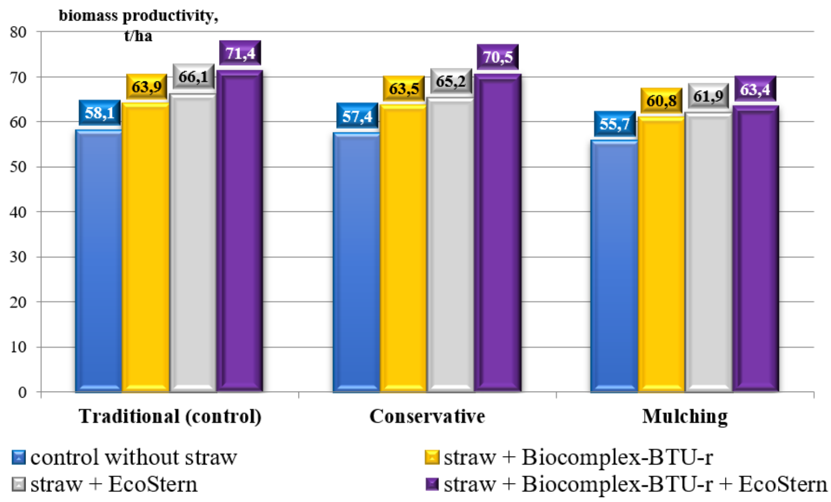

Figure 2. Sugar sorghum biomass yield depending on the technology (tillage method) and the use of straw (average for 2020–2022), t/ha

7.3 t/ha less with the use of EcoStern for straw processing. Therefore, incorporating straw into the soil as an organic fertilizer positively affects the yield of sweet sorghum green biomass.

The impact of the investigated factors on specific quality indicators of sorghum was also determined. In particular, it was found that the sugar content in the stems varied insignificantly depending on the cultivation technology (Table 4).

Under traditional cultivation technology (plowing to a depth of 25–27 cm), the average sugar content in the stems throughout the study was 17.0%, for conservation technology (no-tillage) it decreased by 0.2%, and for mulching (discing) it decreased by 0.5%. This indicator changed more under the influence of the preparations used for straw processing than from the soil treatment method. For example, for the cultivation of the sorghum hybrid on control plots without straw, the total sugar content in the stems was 16.1%. Inoculation of the straw with the Biocomplex-BTU-r biopreparation increased the sugar content by 0.3%, the use of the EcoStern straw destructor increased it by 0.9%, and with the combined use of Biocomplex-BTU-r and EcoStern, it increased by 1.4%.

According to the total sugar content in the stems and the levels of the formed yield, the conditional output (collection) of total sugars from one unit of sorghum cultivation area changed when harvested at the milky-waxy ripeness phase (Figure 3).

Table 4. The content of total sugars in the stems of sugar sorghum plants in the phase of milky-waxy grain maturity depending on the studied factors, % (average for 2020–2022)

No	Soil treatment technology (factor A)	Method of using straw* (factor B)				Average for factor A
		A	B	C	D	
1.	Traditional (control)	16.3	16.6	17.2	17.7	17.0
2.	Conservative	16.2	16.9	16.9	17.5	16.8
3.	Mulching	15.9	16.2	16.8	17.2	16.5
	Average for factor B	16.1	16.4	17.0	17.5	16.8

Note: A – control without straw; B – straw + Biocomplex-BTU-r; C – straw + EcoStern; D – straw + Biocomplex-BTU-r + EcoStern.

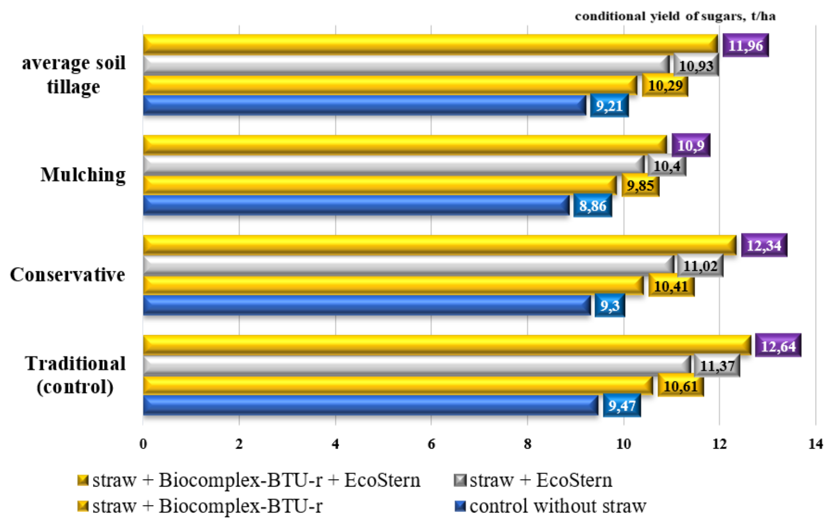

Figure 3. Conditional collection (yield) of total sugars from sowing sugar sorghum depending on the measure of soil cultivation and straw production (average for 2020–2022), t/ha

The conditional output of total sugars from one unit of sorghum cultivation area varied on average across the study from 8.86 t/ha in the variant without the use of straw under mulching technology to 12.64 t/ha for the combination of straw processing + Biocomplex-BTU-r + EcoStern under traditional technology (plowing to a depth of 25–27 cm). Replacing the cultivation of the sorghum hybrid from plowing to chiseling reduced this indicator on average across the study by 0.30 t/ha, and under mulching (discing to a depth of 12–14 cm) by 1.74 t/ha.

The use of straw processing led to an increase in the conditional output of total sugars from one hectare of sorghum cultivation compared to the control without straw (9.21 t/ha): inoculation of the straw with Biocomplex-BTU-r by 1.08 t/ha, with EcoStern by 1.72 t/ha, and with the combination for straw processing of Biocomplex-BTU-r and EcoStern by 2.75 t/ha.

CONCLUSIONS

The generalization of various studies on the effectiveness of using straw as an organic fertilizer has been established, indicating that it can successfully replace manure. Straw is the cheapest organic material that has a positive effect on the accumulation and retention of moisture in the soil, which is extremely important for the Southern Steppe of Ukraine.

High efficiency from fertilizing with straw has also been established in the cultivation of drought-resistant sugar sorghum during 2020–2022 without irrigation using it with a biopreparation and sterna destructor (especially in combination). Regardless of the measure and depth of cultivation, straw as an organic fertilizer enhances the growth processes of sorghum plants, significantly increases the yield of green biomass, the content of total sugars in it, and their conditional output (harvest) per unit area. The yield in the most optimal variant of the study with the application of straw using the Biocomplex BTU-r and EcoStern for inoculation, combined with plowing to a depth of 25–27 cm, increases by 7.3 t/ha, and the conditional sugar harvest by 2.75 t/ha compared to the variant without straw cultivation. However, the most important purpose of straw remains the improvement of the main fertility indicators of the soil, enriching it with fresh organic matter, improving water permeability, and water retention capacity.

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