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Impact of biologized agrotechnology on brown mustard productivity and resource use efficiency

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The agricultural landscape of Kherson Oblast, Ukraine, is increasingly challenged by climatic variability and the imperative for resource-use optimization. To enhance the resilience and sustainability of crop production in this region, a two-year field study was conducted over the 2023–2024 growing seasons to evaluate the effects of three distinct cultivation technologies (Traditional, Biological, and Organic) and three seeding rates (2.0, 2.5, and 3.0 million seeds/ha) on the productive moisture content, nutrient dynamics, and yield of brown mustard (*Brassica juncea*). The results indicated a clear superiority of the biologized agrotechnological systems. The biological and organic technologies consistently maintained significantly higher productive soil moisture reserves throughout the growing season and demonstrated lower average daily water consumption. This translated into superior water-use efficiency, with lower water consumption coefficients (WCC) recorded for the biologized treatments. In addition to water efficiency, these systems exhibited superior nutrient-use efficiency. Regression modeling confirmed a strong relationship between agrotechnology and nitrate uptake ($R^2 = 0.72$), with biological (24.5 kg/t) and organic (23.6 kg/t) systems requiring significantly less nitrate per ton of yield compared to the traditional approach (29.8 kg/t). The impact on phosphorus uptake was more nuanced ($R^2 = 0.39$), with the organic system demonstrating the highest efficiency (60.8 kg/t), highlighting the role of long-term soil health in phosphorus cycling. Furthermore, the study confirmed a quadratic relationship between seeding rate and water consumption, underscoring a critical trade-off between plant density and water use. Ultimately, the resource-efficient biological and organic systems produced significantly higher yields, with top performances reaching 1.57 t/ha of mustard seeds. These findings underscore that biologized practices are not only viable but are superior for optimizing agricultural resources and enhancing crop productivity in semi-arid environments compared to traditional ones. The adoption of biological and organic cultivation technologies presents a clear pathway for building resilient, high-yield agricultural systems capable of withstanding climatic stresses and reducing dependency on external inputs.

Keywords: agroecological modeling; nutrients uptake; organic farming; semi-arid climate; water consumption.

Introduction

A defining characteristic of modern agricultural production across all agro-zones, particularly in the southern Steppe of Ukraine, is a significant imbalance within field agrocenoses. This imbalance is driven by the increasing dominance of high-margin agricultural crops. Unfortunately, these crops often offer economic appeal at the expense of ecological tolerance, leading to concerns about the preservation and enhancement of existing biodiversity. This is primarily due to simplified crop rotations and intensive monoculture practices driven by economic incentives. For example, the expansion of high-profit crops like sunflower, corn, and soybeans disrupts traditional crop rotations, leading to poor starting conditions for subsequent crops (e.g., winter wheat), reduced yields, and increased vulnerability to pests and diseases (Goloborodko et al., 2020). Besides, excessive ploughing and intensive cultivation of profitable crops exceed ecologically acceptable limits, accelerating physical and chemical degradation of soil and reducing long-term productivity. High-intensity farming and monocultures decrease the diversity of economically significant plant species, especially during periods of agricultural intensification. Apart from the mentioned above, monocultures create significant imbalances in the cycling of macro- and microelements, with nutrient extraction exceeding replenishment, leading to soil fertility decline (Tamahina & Turabov, 2021). Also, reduced crop diversity increases weed infestation and the spread of soil-borne diseases, further undermining crop competitiveness and yield, as well as making water resources use less efficient compared to diverse crop rotations (Domaratskiy et al., 2024). Focusing on the technical oilseed crops typical for Steppe crop rotations, the past decade and a half has seen their representation in this agro-climatic zone (under rainfed conditions) almost exclusively limited to two crops: sunflower and winter rapeseed. Only in areas with extensive irrigation can soybean be added to this list (Melnyk et al., 2017).

Considering these factors, it is highly possible that introducing brown mustard (*Brassica juncea*) into field crop rotations offers a vital and potentially singular effective measure to improve the situation in Ukrainian crop rotations. It addresses the increasingly urgent problem, highlighted by domestic scientists, of a deficit of satisfactory and optimal preceding crops for winter wheat. This expansion of suitable crops in field agrocenoses would simultaneously offer high economic efficiency, soil-improving properties, and highly technological cultivation processes (Gadzalo et al., 2020).

The excellent qualities of brown mustard as a preceding crop, its high ecological plasticity, cultivation technology, and relative unpretentiousness to abiotic factors are well-established. In some respects, such as its cold and drought resistance, it stands as a benchmark among spring oilseed crops and has long garnered favor among both farmers both in Ukraine and abroad. In the context of current global warming and gradient increases in drought events, brown mustard's heat and drought tolerance are of great importance to provide sustainable oil production (Lykhovyd, 2021; Kyrychenko, 2024). Brown mustard provides numerous benefits. First, it provides weed suppression. In some experimental studies, it reduced weed density by 56% compared to other crops (Schutte & Toth, 2024). Even considering the inconsistency of this effect, it is an extremely important feature that must be taken into account. Another study reported reduced weed biomass by 50% in 90% of site-years owing to mustard effects (Björkman et al., 2015). Second, the crop possesses antifungal activity. Brown mustard releases volatile compounds, especially allyl isothiocyanate (AITC), which have strong fungistatic effects. High

AITC concentrations from brown mustard can completely inhibit the growth of *Fusarium* pathogens *in vitro* and reduce their negative impact on crops like maize when incorporated into the soil or applied as green manure (Haesaert et al., 2020). The main glucosinolate, sinigrin, and its breakdown products show nematicidal activity, offering potential for natural pest control (Temiz et al., 2024). And finally, brown mustard has a short growing season of about 90 days, making it perfect preceding crop because farmers have an extended period of time after harvesting to perform careful soil tillage for the next crop in the rotation.

As it was noted above, brown mustard provides great opportunities for biologization in the field of crop production because of its potential to suppress weeds and plant pathogens. It is especially important for the systems of biologized and organic farming, which are growing in popularity in the world. Organic and biologized farming are increasingly recognized as sustainable alternatives to conventional agriculture, aiming to improve environmental health, food safety, and long-term productivity. These approaches emphasize ecological processes, reduced chemical inputs, and the use of biological methods to enhance soil fertility and crop resilience, as well as biological plant protection. The global organic food market is expanding rapidly, projected to nearly double from $215 billion in 2023 to over $412 billion by 2027, driven by environmental awareness and health concerns over chemical pesticides (Samanta et al., 2024). As far as biologization involves using biological preparations, rational and diverse crop rotations to restore soil fertility and ecological balance, brown mustard as a low-demanding and promising oilseed crop with a pronounced phytosanitary capacity looks like a highly promising alternative to traditional oil rapeseed and sunflower in the regions with insufficient natural humidification (Nasiyev et al., 2021). Notwithstanding the fact that there is a lack of scientifically sound studies regarding brown mustard use in biologized farming systems, some evidence exists in favor of this approach. For example, no-till and residue management in mustard-based crop systems increased soil organic carbon, improved infiltration, reduced soil bulk density, and enhanced sustainability and productivity of agrophytocenoses. Green manure-mustard and brown manure-mustard systems showed the highest improvements in soil quality and yield (Rathore et al., 2016; Aggarwal et al., 2021). Integrated organic management systems, especially those combining mustard with other crops (e.g., maize, cowpea), improved energy productivity, eco-efficiency, and reduced greenhouse gas intensity (Singh et al., 2022). Use of mustard as a cover crop (including mixtures with oats or as green manure) in organic systems increased soil microbial activity, respiration, and labile carbon pools, contributing to improved soil fertility and sustainability (Saljnikov et al., 2024).

Despite these advantages, a certain bias against brown mustard persists among agricultural producers. In our view, the primary impediment to its widespread adoption, even among producers keen to enhance the ecological status of their agroecosystems, is the unresolved issue of agro-ecological coordination and technological refinement necessary for achieving economically viable yields. It is noteworthy that researchers have devoted considerably less attention to investigating both the individual components of biologized brown mustard cultivation technology and the methodologies for attaining crop yields through contemporary organic principles (Zhuikov, 2013; Ursal & Matviiko, 2020). This limited research, coupled with the high interest in and demand for organic production, underscores the relevance of investigating the effects of agrotechnology biologization on the efficiency of natural resource utilization, particularly water resources and nutrient elements, by brown mustard crops.

Materials and methods

To effectively and thoroughly address the research objectives, we established a classic two-factor, short-term field experiment. This experiment, conducted over the years 2023–2025, featured the following values and gradations for its factorial components:

Factor A (Cultivation Technology) comprised options for growing Sarepta mustard for commercial seeds:

Traditional (intensive) zonal cultivation technology: standard practices for the crop.

Biologized cultivation technology: excluded mineral fertilizers, which were replaced exclusively with organic preparations.

Organic cultivation technology: did not involve mineral fertilizers or synthetic pesticides, instead utilizing organic multi-functional fertilizers and organic pesticides.

Factor B (Seeding Rate) included variants ranging from 2.0 to 3.0 million viable seeds per hectare, with increments of 0.5 million seeds per hectare.

The scientific study was carried out at the State Enterprise "Experimental Farm Pioneer of the Institute of Climate-Smart Agriculture of NAAS" (Lyubymivka village, Beryslav district, Kherson Oblast). Throughout the entire research period, the Prima variety of spring brown mustard (*Brassica juncea*), bred at the Institute of Oilseed Crops of NAAS, was sown in the experiment (Fig. 1).

Soil and climate conditions of the experiment conduction are typical for semi-arid steppe climate. Generally, the zone belongs to the Dfa moderate climate zone with accordance to the Köppen climate classification (Kottek et al., 2006).

The years of the study had some deviations from perennial climatic means for 1991–2020. The year 2023 was consistently warmer than the perennial average for Kherson Oblast, with the most significant deviations occurring in the winter months (December, January, and February) and late autumn (October, November). The average annual temperature for 2023 was notably higher than the long-term norm. July and August recorded maximum temperatures of 38.0 °C and 37.1 °C respectively, which are very close to the historical absolute maximums of 40.5 °C in July and 40.7 °C in August. The maximum temperature of 27.9 °C in October is very high compared to the average daily maximum of 16.1 °C. The historical record for October is 32.0 °C, so 2023 was close to this extreme. The minimum temperatures in January (–8.5 °C) and February (–10.5 °C) were colder than the perennial average minimums of –4.4 and –3.8 °C, but not close to the record lows of –26.3 and –24.4 °C. The minimum temperature in May (3.2 °C) was also close to the historical record low of –1.5 °C for that month, which could be a risk for agriculture. The minimum temperature of –0.1 °C in October is a bit colder than the perennial average minimum of 6.3 °C but is far from the record low of –7.6 °C. The precipitation pattern in 2023 was highly unusual. The first half of the year (January to June) was extremely dry, with no recorded precipitation. This is a significant deviation from the norm and could have a major impact on agriculture and water resources. The summer months (July, August) saw slightly more precipitation than average. November stands out with a very high amount of rainfall, almost three times the perennial average, while September and October were much drier than average. The annual total precipitation was significantly below the perennial norm. In conclusion, the meteorological conditions in Kherson in 2023 were a notable deviation from the perennial norms, characterized by a warmer-than-average year, a severe drought in the first half of the year, and a very wet November.

The year 2024 was exceptionally warm in Kherson Oblast. Almost every month recorded an average temperature significantly higher than the perennial norm. February, April, July, and September stand out with remarkably high deviations, indicating a very mild winter, an unusually hot spring, and a scorching summer. The overall annual average temperature for 2024 is projected to be substantially higher than the long-term average, continuing a trend of warming. July's maximum of +39.3 °C and August's maximum of +36.4 °C are notably high, approaching the historical record highs of +40.5 °C (July) and +40.7 °C (August). April's maximum of +27.0 °C and September's maximum of +33.6 °C are also very high, indicating extended periods of summer-like weather into the shoulder seasons. January's minimum of –13.8 °C and December's minimum of –8.6 °C are significantly colder than the perennial average minimums of –4.4 and –2.2 °C, respectively. However, they are not close to the absolute record lows (–26.3 and –22.2 °C), indicating some cold snaps but not extreme cold on a historical scale. The minimums for the summer months were also higher than the perennial average, leading to warmer nights. Like 2023, 2024 was a dry year overall. The first half of the year (January to July) was significantly drier than the perennial average, with June being particularly dry. This could have negative consequences for agriculture. A notable surplus of precipitation occurred in September and October, which is a significant deviation from the norm for those months, especially October. The total annual precipitation was below the perennial average. In conclusion, the meteorological data for 2024 continues the trend of a warming climate in Kherson, with a significant increase in average temperatures, prolonged dry periods, and calm wind conditions, indicating a further shift away from the established perennial norms. Thus, the trial was performed under relevant and to some extent extreme meteorological conditions, making the obtained results even more valuable for current agricultural science and agroecology, providing the evidence of natural resources use by brown mustard crops under the conditions of increasing aridity.

The soil of the experimental plot was dark-chestnut middle-loamy, with a humus content of 2.3% in the arable layer (0–30 cm). This type of soil is typical for the semi-arid steppe zone conditions.

Soil moisture content was determined using gravimetric method to establish the dynamics of soil moisture and plant water availability at the time of determination. Soil moisture reserves were determined throughout the growing season of the studied crop to find out the dynamics of water use. Sample collection was performed using a soil auger at the major stages of brown mustard growth and development, namely: seedlings, rosette, stemming, budding, flowering, pod formation, pod browning, full ripeness of seeds. Sample collection, weighing, transportation, and storage adhered to the requirements of the stipulated methodology. Soil samples' analysis was performed in the certified laboratory at the Institute of Climate-Smart Agriculture of NAAS (Reynolds, 1970). The total water consumption of brown mustard during the vegetation period was determined by the water balance method using a simplified formula (1):

$$W = O + (Wh - Wk), \qquad (1)$$

where W – total water consumption for the period (m^3/ha); O – atmospheric precipitation for the period (m^3/ha); Wh – moisture reserve in the active soil layer at the beginning of the period (m^3/ha); Wk – moisture reserve in the active soil layer at the end of the period (m^3/ha).

The water consumption coefficient for brown mustard to evaluate the efficiency of freshwater resources usage by brown mustard depending on agrotechnology was calculated using formula (2):

$$WCC = W / Y, \qquad (2)$$

where WCC – water consumption coefficient (m^3/t); W – total water consumption during the vegetation period (m^3/ha); Y – crop yield (t/ha).

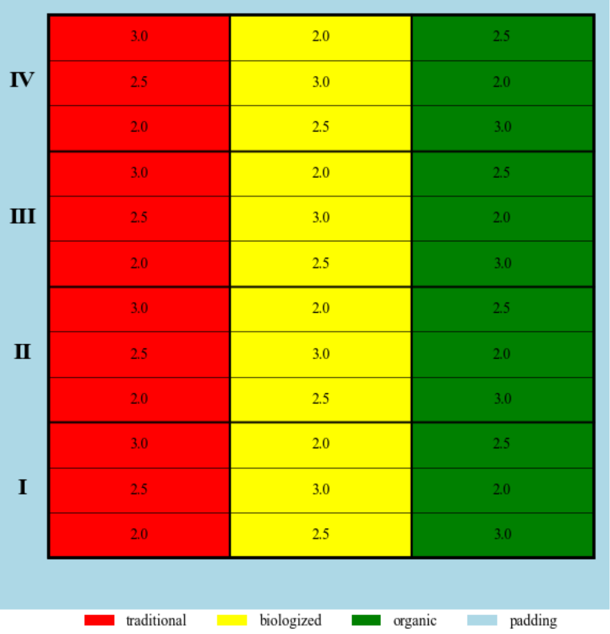
To evaluate the efficiency of soil nutritious elements usage by brown mustard depending on agrotechnology, nitrate nitrogen and mobile phosphorus content were determined. Nitrate nitrogen content was determined by the colorimetric method using a disulfophenolic acid extract (Sah, 1994). Mobile phosphorus was determined by Chirikov's modified method using acetic acid extraction and further photocolorimetry analysis (Voytovyk et al., 2024). Soil samples were analyzed in the certified laboratory at the Institute of Climate-Smart Agriculture of NAAS.

Fig. 1. Brown mustard crops (var. Prima) at budding and full ripeness stages

The field experiment was conducted with four replications, covering a total area of 0.72 hectares. An additional 0.07 hectares were allocated for protective buffer strips. The experiment comprised 36 individual plots (3 levels of Factor A × 3 levels of Factor B × 4 replications). Each first-order experimental plot measured 180 m^2 (50 × 3.6 m), with a harvestable area of 150 m^2 (41.5 × 3.6 m). The experimental design used a split-plot method, where cultivation technologies (Factor A) were assigned to the main plots. The seeding rate variants (Factor B) were partially randomized within these main plots (Fig. 2). Brown mustard agrotechnology in the field trials was represented by the following practices. Across all research years, winter barley served as the preceding crop. After its harvest, the soil was disked to a depth of 10–12 cm using a BDT-7 heavy harrowing unit. Approximately 10–15 days later, mineral fertilizers were applied to the plots designated for traditional cultivation technology. The calculated average application rate over the research period was N72P32. Ammonium nitrate (Grade B) was used as the nitrogen source, and granulated superphosphate for phosphorus.

For the biologized and organic cultivation technologies, organic fertilizers approved for organic farming were applied. Following fertilizer application according to the experimental design, moldboard plowing was performed to a depth of 22–24 cm using a PLN-5-35 plow. This was followed by autumn leveling of the fallow land with a KPE-3.8 anti-erosion cultivator to a depth of 10 cm.

The spring cycle of work began with pre-sowing cultivation using a KPS-4 unit to a depth of 5–6 cm, followed by pre-sowing rolling of the soil with KSh-3 rollers. Depending on the experimental design, elite seeds underwent pre-sowing incrustation with either synthetic or organic complex multi-functional fertilizers, insecticides, and fungicides.



IV	3.0	2.0	2.5
	2.5	3.0	2.0
	2.0	2.5	3.0
III	3.0	2.0	2.5
	2.5	3.0	2.0
	2.0	2.5	3.0
II	3.0	2.0	2.5
	2.5	3.0	2.0
	2.0	2.5	3.0
I	3.0	2.0	2.5
	2.5	3.0	2.0
	2.0	2.5	3.0

Fig. 2. The scheme of field trials on the effects of different agrotechnologies on the efficiency of natural resources usage by the brown mustard crop

Sowing was carried out in early spring when the soil temperature at seed depth (3–5 cm) reached +4–5 °C. A conventional row method was used, with 15 cm row spacing, employing a SZ-3.6A seeding drill. Seeds were sown to a depth of 3 cm, followed by post-sowing rolling with KSh-3 rollers. The seeding rate varied according to the experimental variant and its specific requirements.

Brown mustard crop care focused on controlling pests, diseases, and weeds based on their economic injury levels (EIL). Weed control varied depending on Factor A. Traditional plots received the Galera® post-emergence herbicide at a rate of 0.3 L/ha. Biologized and organic plots relied on mechanical weeding using specialized equipment. Disease and pest control involved following options depending on agrotechnology variant:

Synthetic plant protection products (PPPs): The insecticide Vantex® at 0.05 kg/ha and the fungicide Propulse® at 0.5 L/ha.

Biopreparations approved for organic farming: Oracle® chelated micronutrient fertilizer, Viridin® and Gaubsin Forte® fungicides, and Actoverm® and Naturgard® insecticides.

Insecticidal and fungicidal foliar treatments were applied twice during the growing season, specifically during the "budding" and "pod formation" stages, with a working solution application rate of 200–250 L/ha. When used in combination, tank mixes were prepared no more than 30 minutes before application.

Harvesting was performed by direct (single-phase) combining using a "Sampo-130" combined harvester at the full ripeness stage of brown mustard. The harvested seeds were cleaned and the yields were recalculated to the standard seed moisture of 12%.

We used a two-way analysis of variance (ANOVA) to evaluate the main effects and interactions of our treatment factors. A significance level of P = 0.05 was applied to all analyses. For post-hoc pairwise comparisons, we employed Tukey's Honestly Significant Difference (HSD) test. Treatment means that showed a statistically significant difference ($P < 0.05$) are indicated by different superscript letters (Nanda et al., 2021). Variability within treatments is presented as the mean ± standard deviation. Standard deviations were calculated following established statistical protocols (Kurtz et al., 1979). The relationships between brown mustard sowing rates and agrotechnology and water consumption coefficient and nutrients' uptake were investigated using quadratic regression model and multiple linear regression model with previous transformation of categorical values into dummy format (Su et al., 2012). All statistical computations were performed using a custom script in Python 3.13, leveraging external libraries such as numpy, pandas, matplotlib, and sklearn.

Results

The modern practice of widely applying elements of biologization in zonal crop cultivation technologies is, for the most part, aimed at optimizing the supply of essential ecological factors for plant life. Among these, water supply stands out, especially given the specific characteristics of the cultivation zone.

The consistently high initial productive moisture content at the "Seedlings" stage (1564 m^3/ha) across all treatments indicates a uniform starting point. The subsequent progressive decline in moisture content throughout the growing season, reaching its lowest point at "Full Seed Ripeness," is a natural physiological process reflecting the evapotranspiration of the crop. The consistent and significant differences observed across the growth stages highlight that both cultivation technology and seeding rate are significant factors influencing the productive moisture content of the soil. The magnitude of the moisture decline is a direct measure of the crop's water consumption, which is in turn affected by these management practices (Table 1).

Table 1

Dynamics of productive moisture content in the one-meter soil layer of brown mustard crops depending on cultivation technology and seeding rate (m^3/ha, average for 2023–2024, mean ± standard deviation, n = 4)

Cultivation technology	Seed sowing rate, million pieces/ha	Brown mustard growth stages							
		seedlings	rosette	stemming	budding	flowering	pod formation	pod browning	full ripeness
Traditional	2.0	1564.2 ± 46.9^{a}	1327.2 ± 39.8^{a}	1224.2 ± 36.8^{a}	1009.2 ± 36.7^{a}	876.2 ± 30.3^{a}	774.0 ± 26.3^{bc}	424.3 ± 13.2^{bc}	284.2 ± 12.7^{bc}
	2.5	1564.0 ± 46.2^{a}	1269.1 ± 38.1^{b}	1186.1 ± 38.1^{b}	896.3 ± 35.6^{b}	802.2 ± 26.9^{b}	722.1 ± 24.1^{d}	402.2 ± 11.7^{d}	241.0 ± 12.1^{c}
	3.0	1563.8 ± 44.9^{a}	1280.4 ± 38.4^{b}	1111.8 ± 33.4^{c}	860.1 ± 25.8^{c}	777.0 ± 23.3^{d}	703.3 ± 21.1^{d}	388.1 ± 11.6^{c}	216.3 ± 6.5^{e}
Biological	2.0	1564.2 ± 46.5^{a}	1312.9 ± 39.4^{a}	1266.0 ± 38.0^{ab}	1064.0 ± 31.9^{d}	911.3 ± 27.3^{ab}	826.0 ± 24.8^{a}	455.4 ± 13.7^{ab}	349.1 ± 10.5^{a}
	2.5	1564.3 ± 47.2^{a}	1307.1 ± 39.2^{a}	1202.0 ± 36.1^{b}	922.2 ± 27.7^{e}	874.4 ± 26.2^{bc}	798.8 ± 24.0^{ab}	423.8 ± 12.7^{bc}	311.0 ± 9.3^{bc}
	3.0	1564.2 ± 46.9^{a}	1288.2 ± 38.6^{ab}	1191.3 ± 35.7^{b}	887.0 ± 26.6^{e}	821.0 ± 24.6^{cd}	733.2 ± 22.0^{cd}	388.8 ± 11.7^{c}	271.2 ± 8.1^{d}
Organic	2.0	1564.0 ± 45.5^{a}	1255.4 ± 37.7^{b}	1282.2 ± 38.5^{a}	1069.8 ± 32.1^{d}	930.4 ± 27.9^{a}	819.0 ± 24.6^{a}	462.2 ± 13.9^{a}	342.3 ± 10.3^{ab}
	2.5	1563.8 ± 44.7^{a}	1296.8 ± 38.9^{ab}	1252.0 ± 37.6^{ab}	940.8 ± 28.2^{e}	900.1 ± 27.0^{ab}	796.0 ± 23.9^{ab}	422.1 ± 12.7^{bc}	320.0 ± 9.6^{ab}
	3.0	1564.0 ± 46.8^{a}	1290.7 ± 38.7^{ab}	1183.9 ± 35.5^{b}	903.0 ± 27.1^{e}	855.0 ± 25.7^{bc}	751.0 ± 22.5^{bc}	397.0 ± 11.9^{c}	283.0 ± 8.5^{cd}

Note: different superscript letters mean that there is a statistically significant difference between the variants of the experiment within the column according to the results of ANOVA with Tukey's post-hoc test at $P < 0.05$.

Comparing the treatments at later stages, such as "Pod Formation" and "Full Seed Ripeness," biological and organic technologies generally maintain a higher moisture content than traditional cultivation technology. At "Full Seed Ripeness," the traditional treatments consistently show the lowest moisture levels. This improved moisture retention is a hallmark of agroecological systems. It suggests that biological and organic technologies have enhanced the soil's physical properties. The higher moisture content in the biological and organic systems, especially during peak water demand stages like "Flowering" and "Pod Formation," could also indicate a more efficient use of water by the crop. This could be due to a more robust root system in healthier soil, enabling the plant to access water more effectively, or a better microclimate within the canopy that reduces water loss. The significantly higher moisture content at "Full Seed Ripeness" suggests a greater residual moisture reserve, which could be beneficial for subsequent crops or for mitigating the effects of drought.

Across all three cultivation technologies, an increase in the seeding rate (from 2.0 to 3.0 million pieces/ha) consistently leads to a greater reduction in soil moisture content. This is a classic ecological principle. A higher plant density per unit area results in a greater number of individual plants competing for the same limited resources, including soil moisture. The cumulative effect of transpiration from a denser crop canopy is a more rapid and pronounced depletion of the soil water reservoir. The findings have significant implications for agricultural resource optimization, particularly in regions with limited water availability, like Kherson Oblast. In such environments, a higher seeding rate, while potentially leading to a higher yield under optimal conditions, can be a major risk factor during dry spells. Table 1 shows that at the end of the season, the difference in remaining moisture between the 2.0 and 3.0 million seeds/ha rates is substantial.

Table 2 is a complement to Table 1, as it quantifies the water use efficiency of different cultivation strategies. It provides a clear picture of the total water consumed and the average daily consumption, allowing a direct comparison of the treatments. The most striking insight from the table is the clear water-saving advantage of the "Biological" and "Organic" cultivation technologies compared to the "Traditional" method. Across all corresponding seeding rates, the total water consumption and average daily consumption are statistically significantly lower for the biological and organic treatments. This finding is particularly significant for Kherson Oblast and other similar regions with semi-arid climate, which experience hot, dry summers. A lower average daily consumption rate means the crop is less susceptible to short-term drought stress. Biological and organic technologies enable the crop to "stretch" its available water reserves over the growing season, mitigating the risk of critical moisture deficits during sensitive growth stages like flowering and pod formation.

Table 2
Average daily soil moisture consumption by brown mustard plants depending on cultivation technology and seeding rate (m^3/ha, average for 2023–2024, mean ± standard deviation, n = 4)

Cultivation technology	Seed sowing rate, million pieces/ha	Active moisture reserve at seedlings	Active moisture reserve at full ripeness	Total water consumption	Average daily consumption
Traditional	2.0	1564.2 ± 46.9^{a}	284.2 ± 12.7^{bc}	1280.0 ± 64.0^{c}	14.4 ± 0.7^{c}
	2.5	1564.0 ± 46.2^{a}	241.0 ± 12.1^{c}	1323.0 ± 66.2^{ab}	15.2 ± 0.8^{ab}
	3.0	1563.8 ± 44.9^{a}	216.3 ± 6.5^{e}	1347.5 ± 67.4^{a}	15.7 ± 0.8^{a}
Biological	2.0	1564.2 ± 46.5^{a}	349.1 ± 10.5^{a}	1215.1 ± 60.7^{e}	13.3 ± 0.7^{e}
	2.5	1564.3 ± 47.2^{a}	311.0 ± 9.3^{bc}	1253.3 ± 62.6^{d}	13.9 ± 0.7^{d}
	3.0	1564.2 ± 46.9^{a}	271.2 ± 8.1^{d}	1293.0 ± 64.7^{bc}	14.5 ± 0.7^{bc}
Organic	2.0	1564.0 ± 45.5^{a}	342.3 ± 10.3^{ab}	1221.7 ± 61.1^{e}	13.1 ± 0.7^{e}
	2.5	1563.8 ± 44.7^{a}	320.0 ± 9.6^{ab}	1243.8 ± 62.2^{d}	13.4 ± 0.7^{e}
	3.0	1564.0 ± 46.8^{a}	283.0 ± 8.5^{cd}	1281.0 ± 64.0^{c}	14.1 ± 0.7^{cd}

Note: refer to Table 1 for ANOVA interpretation.

Within each cultivation technology, as the seeding rate increases from 2.0 to 3.0 million pieces/ha, the total water consumption and average daily consumption also increase. This phenomenon is a direct consequence of inter-plant competition for resources. A higher plant density results in greater cumulative leaf area and biomass, leading to increased transpiration from the crop canopy. This intensified competition for water can lead to more rapid depletion of soil moisture, especially during peak growth periods. This insight is vital for natural resource usage optimization. While a higher seeding rate might be desirable for maximizing yield potential under ideal conditions, the data clearly shows the water penalty associated with it. In a water-limited environment, the optimal seeding rate is not necessarily the highest one.

Water consumption coefficient (WCC) is a critical agroecological metric, defined as the volume of water consumed per unit of yield. A lower WCC indicates higher water-use efficiency – meaning the crop produces more biomass or yield for every cubic meter of water it consumes. It was determined that the highest seed yields of brown mustard were harvested under biological cultivation technology at the seeding rate of 2.5 million pieces/ha and under Organic farming with the seeding rates of 2.5–3.0 million pieces/ha. Considering that the difference between 2.5 and 3.0 seeding rates options is insignificant (0.01 t/ha), the seeding rate of 2.5 million pieces/ha should be preferred as it provides the best water use efficiency in accordance with the WCC values. Notwithstanding the fact that the lowest WCC was recorded under traditional agrotechnology and this difference is statistically significant, the yield of brown mustard seeds was significantly lower (by 0.31 t/ha) than under organic and biological farming. On average, the best water use efficiency was provided by organic agrotechnology (1055 m^3/t) followed by biological (1098 m^3/t) and Traditional (1121 m^3/t) cultivation technologies of brown mustard. Quite logically, increased seeding rates led to increased water consumption and higher WCC values, but a reasonable increase in seeding rates was established only for switching from 2.0 to 2.5 million pieces/ha. Further increment to 3.0 million pieces/ha results in inefficient water consumption and decreased yields of seeds (Table 3).

Table 3
Yield of conditional seeds of brown mustard and water consumption coefficient depending on cultivation technology and seeding rate (average for 2023–2024, mean ± standard deviation, n = 4)

Cultivation technology	Seed sowing rate, million pieces/ha	Yield of conditional seeds, t/ha	Water consumption coefficient, m^3/t of seeds
Traditional	2.0	1.12 ± 0.21^{e}	1212.2 ± 60.6^{e}
	2.5	1.25 ± 0.05^{d}	1013.9 ± 50.7^{d}
	3.0	1.14 ± 0.16^{e}	1136.8 ± 56.8^{e}
Biological	2.0	1.41 ± 0.08^{b}	1136.6 ± 56.9^{b}
	2.5	1.56 ± 0.19^{a}	1069.3 ± 53.5^{a}
	3.0	1.32 ± 0.04^{c}	1089.4 ± 54.4^{c}
Organic	2.0	1.39 ± 0.03^{b}	1107.7 ± 55.4^{b}
	2.5	1.56 ± 0.16^{a}	1020.3 ± 51.0^{a}
	3.0	1.57 ± 0.07^{a}	1038.4 ± 51.9^{a}

Note: refer to Table 1 for ANOVA interpretation.

As for the efficiency of soil nutrients use, dynamical monitoring of nitrate nitrogen and mobile phosphorus content under brown mustard crops was performed. First, nitrate nitrogen dynamics were investigated (Table 4). At the seedlings stage, the nitrate content is relatively uniform across all treatments, ranging from 2.89 to 3.03 mg/kg. This indicates a consistent starting point for the soil's nitrogen supply. In traditional cultivation technology, there is a clear and consistent decline in nitrate content from the seedlings stage to full ripeness. The decline is linear and steady, reflecting the continuous uptake of nitrogen by the growing crop. By the time the crop reaches stemming, the nitrate levels are significantly lower than in the biological and organic systems. In the biological and organic systems, the nitrate content either remains stable or, more notably, increases or holds steady during the early crop growth stages. The increase or stability of nitrate levels during the early growth stages in the biological and organic systems is a clear indicator of active and healthy nitrogen cycling. Unlike the Traditional system, where nitrogen is simply consumed from a finite pool, the biological and organic systems are actively mineralizing organic nitrogen into plant-available nitrate. This is a direct result of enhanced soil microbial activity, which is a cornerstone of agroecology. As for the impact of seeding rates, a higher rate leads to a higher plant density and thus a greater total demand for nitrogen. However, the effect of cultivation technology on nitrate dynamics is much more significant than the effect of seeding rate.

Table 4
Dynamics of nitrate nitrogen content in the soil under brown mustard crops depending on cultivation technology and seeding rate (mg/kg, average for 2023–2024, mean ± standard deviation, n = 4)

Cultivation technology	Seed sowing rate, million pieces/ha	Brown mustard growth stages						
		seedlings	rosette	stemming	budding	flowering	pod formation	full ripeness
Traditional	2.0	3.03 ± 0.15^{a}	2.73 ± 0.14^{a}	2.52 ± 0.13^{b}	2.42 ± 0.12^{a}	2.04 ± 0.10^{a}	1.81 ± 0.09^{a}	1.56 ± 0.08^{a}
	2.5	3.02 ± 0.15^{a}	2.66 ± 0.13^{a}	2.43 ± 0.12^{b}	2.33 ± 0.12^{a}	2.03 ± 0.10^{a}	1.74 ± 0.09^{a}	1.71 ± 0.09^{a}
	3.0	2.91 ± 0.15^{a}	2.60 ± 0.13^{a}	2.31 ± 0.12^{a}	2.26 ± 0.11^{a}	2.01 ± 0.10^{a}	1.62 ± 0.08^{a}	1.32 ± 0.07^{a}
Biological	2.0	2.96 ± 0.15^{a}	2.99 ± 0.15^{b}	3.06 ± 0.15^{c}	2.81 ± 0.14^{c}	2.16 ± 0.11^{a}	2.07 ± 0.10^{b}	1.96 ± 0.10^{b}
	2.5	3.00 ± 0.15^{a}	3.04 ± 0.15^{b}	3.05 ± 0.15^{c}	2.69 ± 0.13^{b}	2.10 ± 0.11^{a}	2.06 ± 0.10^{b}	1.89 ± 0.09^{b}
	3.0	2.89 ± 0.14^{a}	2.92 ± 0.15^{b}	2.96 ± 0.15^{c}	2.59 ± 0.13^{b}	2.02 ± 0.10^{a}	1.81 ± 0.09^{a}	1.64 ± 0.08^{a}
Organic	2.0	2.94 ± 0.15^{a}	2.98 ± 0.15^{b}	3.11 ± 0.16^{c}	2.88 ± 0.14^{c}	2.12 ± 0.11^{a}	2.02 ± 0.10^{b}	2.02 ± 0.10^{b}
	2.5	2.89 ± 0.14^{a}	2.93 ± 0.15^{b}	3.01 ± 0.15^{c}	2.70 ± 0.14^{b}	2.07 ± 0.10^{a}	2.00 ± 0.10^{b}	1.92 ± 0.10^{b}
	3.0	2.90 ± 0.15^{a}	2.90 ± 0.15^{b}	2.95 ± 0.15^{c}	2.57 ± 0.13^{b}	1.96 ± 0.10^{a}	1.83 ± 0.09^{a}	1.58 ± 0.08^{a}

Note: refer to Table 1 for ANOVA interpretation.

As for mobile phosphorus content, dynamical monitoring of its quantity in the soil of experimental plots allowed us to reveal following regularities. Beforehand, it should be noted that unlike nitrate, which is highly mobile and prone to leaching, phosphorus is far less mobile and often becomes "fixed" or unavailable in the soil, making its dynamics a direct reflection of soil health and nutrient cycling processes. The data of Table 5 show a clear and expected trend across all treatments: a progressive decline in mobile phosphorus content from the seedlings stage to full ripeness. At early stages, very subtle and mostly insignificant differences between the treatments are observed. However, at later stages of the crop growth the difference becomes not just subtle, but statistically significant. At pod formation and full ripeness stages biological and organic treatments consistently maintained significantly higher residual mobile phosphorus levels compared to traditional agrotechnology. This is a crucial finding for long-term soil fertility and sustainability. It demonstrates that biologized agricultural systems are superior at retaining phosphorus in a plant-available form throughout the growing season. Like the nitrate data, the impact of seeding rate on mobile phosphorus content is less dominant than cultivation technology. While there is a general trend of lower P-levels at higher seeding rates (due to increased plant uptake), the statistical differences are not as consistent as they were for water consumption. This reinforces the idea that the dominant driver of nutrient availability is the health and biological activity of the soil, not simply the density of plants.

Table 5
Dynamics of mobile phosphorus content in the soil under brown mustard crops depending on cultivation technology and seeding rate (mg/kg, average for 2023–2024, mean ± standard deviation, n = 4)

Cultivation technology	Seed sowing rate, million pieces/ha	Brown mustard growth stages						
		seedlings	rosette	stemming	seedlings	flowering	pod formation	seedlings
Traditional	2.0	8.36 ± 0.42^{a}	8.22 ± 0.41^{c}	7.79 ± 0.39^{c}	7.43 ± 0.37^{c}	6.70 ± 0.34^{b}	5.77 ± 0.29^{a}	5.33 ± 0.27^{a}
	2.5	8.32 ± 0.42^{a}	8.20 ± 0.41^{c}	7.62 ± 0.38^{b}	7.40 ± 0.37^{c}	6.41 ± 0.32^{a}	5.60 ± 0.28^{a}	5.20 ± 0.26^{a}
	3.0	8.28 ± 0.41^{a}	8.08 ± 0.40^{b}	7.50 ± 0.38^{a}	7.22 ± 0.36^{a}	6.21 ± 0.31^{a}	5.56 ± 0.28^{a}	5.12 ± 0.26^{a}
Biological	2.0	8.30 ± 0.42^{a}	8.11 ± 0.41^{b}	7.55 ± 0.38^{b}	7.34 ± 0.37^{b}	6.81 ± 0.34^{b}	6.33 ± 0.32^{b}	5.88 ± 0.29^{c}
	2.5	8.33 ± 0.42^{a}	8.04 ± 0.40^{b}	7.46 ± 0.37^{a}	7.19 ± 0.36^{a}	6.76 ± 0.34^{b}	6.21 ± 0.31^{b}	5.81 ± 0.29^{c}
	3.0	8.35 ± 0.42^{a}	7.77 ± 0.39^{a}	7.38 ± 0.37^{a}	7.10 ± 0.36^{a}	6.60 ± 0.33^{b}	6.09 ± 0.30^{b}	5.52 ± 0.28^{b}
Organic	2.0	8.41 ± 0.42^{a}	7.97 ± 0.40^{b}	7.53 ± 0.38^{b}	7.27 ± 0.36^{b}	6.82 ± 0.34^{b}	6.40 ± 0.32^{b}	5.97 ± 0.30^{c}
	2.5	8.42 ± 0.42^{a}	8.00 ± 0.40^{b}	7.43 ± 0.37^{a}	7.15 ± 0.36^{a}	6.72 ± 0.34^{b}	6.29 ± 0.31^{b}	5.86 ± 0.29^{c}
	3.0	8.29 ± 0.41^{a}	7.50 ± 0.38^{a}	7.30 ± 0.37^{a}	7.05 ± 0.35^{a}	6.62 ± 0.33^{b}	6.16 ± 0.31^{b}	5.70 ± 0.29^{b}

Note: refer to Table 1 for ANOVA interpretation.

Finally, the uptake of nitrates and phosphorus by brown mustard depending on agrotechnology was studied (Table 6).

Table 6
Nitrates and phosphorus uptake by brown mustard crops depending on cultivation technology (kg/t, average for 2023–2024, mean ± standard deviation, n = 4)

Cultivation technology	Nitrates uptake	Phosphorus uptake
Traditional	29.8 ± 2.9^{a}	63.5 ± 2.1^{a}
Biological	24.5 ± 1.7^{b}	63.6 ± 2.1^{a}
Organic	23.6 ± 2.5^{b}	60.8 ± 2.1^{b}

It was revealed that the biological (24.5 kg/t) and organic (23.6 kg/t) technologies are significantly more nitrogen-efficient than the traditional technology (29.8 kg/t), as indicated by the statistical difference. Organic technology demonstrates the highest phosphorus-use efficiency, requiring only 60.8 kg/t, which is statistically superior to both the traditional and biological systems. Surprisingly, traditional and biological technologies show statistically similar phosphorus uptake coefficients (63.5 and 63.6 kg/t, respectively).

Regression modeling was employed to quantify the relationships between brown mustard cultivation parameters and resource consumption efficiency. Quadratic regression revealed a moderate connection ($R^2 = 0.41$) between seeding rates and water consumption, while multiple linear regression showed a strong relationship ($R^2 = 0.72$) between agrotechnology and nitrate uptake. The models developed provide valuable insights for optimizing resource use in agricultural systems. Table 7 summarizes the derived regression equations and their associated metrics.

The model explains only 39% of the variability in phosphorus uptake. This is a moderate-to-weak connection, which contrasts sharply with the strong connection ($R^2 = 0.72$) we observed for nitrate uptake using the same independent variable (agrotechnology). This is the most important finding. The model correctly identifies that agrotechnology has a less direct and pronounced effect on phosphorus uptake than it does on nitrate uptake. This aligns perfectly with the statistical analysis of the raw data, which showed that the differences in phosphorus uptake were less statistically significant across the treatments, with only the organic technology showing a clear difference. This low R^2 in this case could be not a sign of a "bad" model; it's a sign that the relationship itself is weaker. In conclusion, the model is good in that it is statistically sound. However, its low R^2 is actually its most valuable output from an agroecological perspective. It serves as a scientific confirmation that improving phosphorus availability is a more complex and long-term process than optimizing nitrogen availability. This is a critical lesson for any agricultural scientist advising on resource optimization and building long-term soil resilience in regions like Kherson Oblast.

Table 7
Regression models for water consumption, nitrate uptake, and phosphorus uptake in brown mustard cultivation

Dependent variables	Equation	R^2	RMSE	MAPE	Explanation of the arguments for each equation:
Water consumption coefficient (WCC), m^3/t of seeds	$WCC = 3341.00 – 1781.00×SR + 343.33×SR^2$	0.41	58.30 m^3/t of seeds	4.39%	SR: seeding rate of brown mustard, million pieces/ha
Nitrates uptake (NU), kg/t of seeds	NU = 24.50(O) – 0.90×T + 5.30×B	0.72	1.70 kg/t of seeds	6.08%	T: "Traditional" agrotechnology; B: "Biological" agrotechnology; O: "Organic" agrotechnology (intercept represents mean NU for "Organic" category; coefficients for other technologies represent deviations from this reference)
Phosphorus uptake (PU), kg/t of seeds	PU = 63.60(O) – 2.80×T–0.10×B	0.39	1.61 kg/t of seeds	2.48%	

Discussion

This study provides compelling evidence in support of biologized agrotechnologies. From an agro-ecological perspective, biologization promotes the sustainable development of agricultural ecosystems by enhancing the allocation and efficiency of natural resource use, including freshwater and soil nutrients, which are primary drivers of crop productivity. A general summary of the results of the current research, main effects of agrotechnological practices on brown mustard productivity and enhanced efficiency of natural resources management in crop production at the expense of cultivation technology biologization are presented in Table 8.

Table 8
Final summary and synthesis of agrotechnological effects on brown mustard productivity and natural resources usage efficiency

Metric	Traditional technology	Biological technology	Organic technology	Agroecological interpretation
Water consumption	high (15.7 m^3/day)	lower (13.3 m^3/day)	lowest (13.1 m^3/day)	superior water retention and reduced evapotranspiration due to improved soil health
Nitrate dynamics	steady depletion	stable/increased early, active cycling	stable/increased early, active cycling	biologically-driven nutrient synchronization matches crop demand, reducing waste
Phosphorus dynamics	steady depletion, high fixation	better retention, some solubilization	best retention, high solubilization	superior soil biology keeps P in a plant-available form.
Yield	lower (1.12–1.25 t/ha)	higher (1.32–1.56 t/ha)	highest (1.39–1.57 t/ha)	improved resource availability (water, N, P) translates directly to higher productivity
Water consumption coefficient (WCC)	high (1014–1212 m^3/t of seeds)	lower (1069–1137 m^3/t of seeds)	lowest (1020–1108 m^3/t of seeds)	the most water-efficient systems produce more yield per cubic meter of water
Nitrate uptake	high (29.8 kg/t of seeds)	lower (24.5 kg/t of seeds)	lowest (23.6 kg/t of seeds)	the most nitrogen-efficient systems produce more yield per kilogram of nitrogen
Phosphorus uptake	high (63.5 kg/t of seeds)	high (63.6 kg/t of seeds)	lowest (60.8 kg/t of seeds)	organic system has a uniquely efficient P-solubilizing capacity, reducing P requirements

It became clear enough that traditional cultivation technology provided no productivity benefits under simultaneous depletion of nutrients in the soil and inefficient water consumption, leading to irrational use of natural resources in agriculture, while biologized approaches and especially organic farming provided the best yields of brown mustard under simultaneous resource-saving.

Our research demonstrates that biologized agricultural practices significantly reduce water consumption and the uptake of nitrate nitrogen and mobile phosphorus from the soil by brown mustard crops. Notwithstanding the claim that organic and biological farming systems can lead to a drastic decrease in food production and threaten food security (Borghino et al., 2024), our results testify that biological and organic farming technologies led to significantly higher yields of brown mustard seeds, supporting the assertion that biologized agriculture offers substantial benefits for food security. To further assess the efficiency of these systems, we analyzed and summarized recent scientific studies on various agricultural crops from different agro-climatic zones.

While most research consistently indicates that crop yields in organic and ecologically intensive farming systems are generally 18% to 35% lower than those in conventional systems, depending on the crop, climate, and management practices, this is not always the case (Kirchmann, 2019). For instance, long-term studies like the DOK trial in Switzerland confirm that organic systems produce 13–34% lower yields for non-legumes, although legume yields often remain comparable (Mayer et al., 2023). Besides, one of the recent studies revealed that inorganic farming practices tend to outperform organic farming systems just in the very beginning, but after 15 years of conversion to biologized practices, organic cultivation systems become even more productive than traditional ones, providing 43.91% higher net profit as well as various environmental benefits (Sahu et al., 2024). Also, it should be stressed that soil health is foundational for sustainable agriculture, requiring integrated management of soil properties, microbial ecosystems, and precision technologies to enhance productivity while mitigating environmental impacts, and the best soil health preservation is usually achieved under biologized agricultural systems, which in a long run will out repay crop producers with better sustainability and resilience to biotic and abiotic stresses and result in better yields quality and decreased losses (Xing et al., 2025).

Current scientific evidence suggests that this yield gap can narrow over time as soil health improves under organic management. In certain rainfed or tropical conditions, organic yields may even approach or surpass conventional yields, especially when soil microbial communities are enhanced (Prabhakar et al., 2023). Our study exemplifies this, showing that brown mustard yields in semi-arid, rainfed conditions can be significantly higher under biologized agriculture than with traditional intensive agrotechnology.

Supporting our findings, other studies demonstrate similar benefits. For example, the application of biologized technology to winter wheat resulted in a seed yield increase of 0.34 t/ha over basic technology and 0.30 t/ha over energy-intensive technology. Additionally, the seeds from the biologized system had superior germination rates (Konovalov et al., 2023). Similarly, the use of Groundfix soil biofertilizer in soybean cultivation increased crop productivity by 117.4% and improved profitability by reducing the need for mineral fertilizers by 30%, while also enhancing soil health and fertility (Didur, 2023).

From an agro-ecological perspective, biologized cultivation technologies significantly increase soil microbial activity, which supports nutrient cycling and long-term fertility. Ivaniv et al. (2024) found that incorporating a biologization element into the mineral nutrition of sunflower in the non-irrigated southern steppe of Ukraine significantly improved nitrogen use efficiency and economic profitability. These organic practices also reduced sunflower water consumption to 407–423 m^3/t and enhanced soil microbiological activity by 40.9%, leading to better natural resource management and environmental stability. These examples confirm that a biological approach to crop production in the extreme conditions of rainfed steppe zones – known for high moisture deficits and heat – provides major benefits for both crop producers and the environment, especially considering the general tendency to freshwater resources scarcity and looking for the approaches to optimize irrigation rates to achieve the best performance at the least expenditures (Vozhehova et al., 2019).

Barbieri et al. (2017) highlight another significant benefit of biologized agriculture: it promotes the inclusion of a wider range of crops in rotations, which makes agricultural systems more diverse, versatile, and flexible. Furthermore, organic and biological farming systems are known to provide protection against soil erosion and nutrient leaching (Mander et al., 1999). By leveraging natural processes like biological nitrogen fixation and the use of beneficial insects for pest control, biological agriculture reduces the reliance on synthetic fertilizers and pesticides. This, in turn, lowers pollution and mitigates negative impacts on non-target species and human health. Biological control methods have also proven effective in managing invasive pests, leading to both environmental and economic gains by reducing crop losses and chemical inputs (Gurr et al., 2018; Vásquez & Colmenárez, 2024). However, challenges remain, such as managing potential risks from organic waste recycling and ensuring the safe use of biopesticides (De Clerck et al., 2024).

It is a well-established scientific fact that biological and organic farming systems increase soil organic carbon levels, contributing to the sustainable development of agricultural ecosystems (Sahu et al., 2024). A global meta-analysis revealed that organic farming promotes biotic abundance, richness, and biodiversity while preserving fertility (Taylor et al., 2019). However, it may also lead to productivity uncertainty due to a greater vulnerability to agricultural stresses. Mayer et al. (2023) support this viewpoint, noting that organic systems tend to have greater yield variability and lower yield stability compared to conventional systems, which can be a food security challenge. Despite these yield differences, organic farming provides significant environmental benefits, including improved soil fertility, higher biodiversity, reduced inputs, and better soil structure (Haan et al., 2018).

Strategies to increase organic yields – such as improved nutrient management, pest control, and crop breeding – carry both risks and opportunities for sustainability and must be managed carefully to avoid negative side effects. While organic and biological systems may not consistently match conventional yields, they contribute to sustainability and can be optimized for better performance in specific contexts (Watson et al., 2018). Overall, biological agriculture represents a promising approach to balancing food production with ecological sustainability and resilience to modern challenges. Apart from the already mentioned benefits, biologized agriculture results in better biodiversity conservation in agriculture, which in its turn boosts productivity and climate resilience of agroecosystems. However, it requires systemic shifts in practices, policies, and economic incentives to overcome existing barriers for food security satisfaction (Wan et al., 2024).

Conclusions

The results of the study provide a clear, quantitative roadmap for a strategic transition in agricultural practices. Traditional cultivation system is demonstrably inefficient both in ecological suitability and crop productivity terms. It requires more water and more nitrogen to produce a lower yield, making it highly vulnerable to climate shocks and rising input costs. It relies on a "brute-force" approach of external inputs to compensate for a degraded soil system. Biologized agrotechnology is a significant step forward. It shows immediate and substantial improvements in water and nitrogen efficiency, leading to higher yields and better natural resources management. Organic farming system is the pinnacle of resource optimization. It excels across all metrics – water, nitrogen, and phosphorus use efficiency – demonstrating a synergistic relationship between soil health, nutrient cycling, and crop productivity. It is the most resilient and sustainable model, capable of producing high yields while reducing dependency on scarce resources and external inputs. In an environment facing climate change, natural resource scarcity, and geopolitical instability, positive impacts of agricultural biologization are invaluable. The results of the study show that by investing in soil health, farmers, who carry out crop cultivation in the zones of risky agriculture, can not only enhance the productivity of their land but also build a more resilient, efficient, and profitable agricultural enterprise for the long term. This is a textbook example of agroecology in action. Further research will be focused on quantifying the long-term ecosystemic benefits, including biodiversity and carbon sequestration, which are possible to achieve through agrotechnology biologization. Detailed economic analysis of biologized agriculture efficiency is also needed to assess the scalability and adoption barriers of such crop cultivation systems, considering specific interventions and market dynamics. Finally, rigorous studies of climate impacts of biologized agricultural practices is also needed to provide for comprehensive evaluation of the benefits and drawbacks of biologized and organic agriculture.

The authors declare that they have no potential conflict of interests.

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