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Ecological characteristics of productivity formation in winter Brassicaceae crops under different fertilization rates

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ABSTRACT

The article presents the results of a study on the productivity of winter crops from the Brassicaceae family under different fertilization rates and the influence of agroecological factors during the growing seasons. The experiments were conducted in 2019–2023 at the Nizhyn Agrotechnical Institute, a separate unit of the National University of Life and Environmental Sciences of Ukraine (Chernihiv region). Wintercress (*Barbarea vulgaris*) cv. Oriana, winter rapeseed hybrid Mercedes, and typhon (*B. rapa* ssp. *oleifera f. biennis* × *(B. rapa* ssp. *rapifera* × *B. rapa* ssp. *pekinensis*)) cv. Orakam were cultivated with 15 cm row spacing under three fertilization regimes: no fertilizer (control), $N_{80}P_{60}K_{60}$, and $N_{120}P_{90}K_{90}$. Among all the Brassicaceae crops studied, typhon showed the best seed yield (3.89 t/ha) under the $N_{80}P_{60}K_{60}$ fertilization rate. While both field cress and rapeseed responded positively to additional fertilization, their yield increases of 0.11 and 0.17 t/ha respectively did not justify the costs of additional mineral fertilizer. Typhon also showed a lower yield response under the higher $N_{120}P_{90}K_{90}$ rate compared to the moderate $N_{80}P_{60}K_{60}$ rate. Energy output from aboveground biomass and oil yield from *Brassicaceae* seeds were significantly influenced by the fertilization regime. These parameters increased with higher fertilization rates – from $N_{80}P_{60}K_{60}$ to $N_{120}P_{90}K_{90}$. However, the economic efficiency of increasing fertilizer doses requires separate analysis. The study showed that the best conditions for realizing the biological potential and achieving high seed yield and energy output in the aboveground biomass of typhon cv. Orakam and the winter rapeseed hybrid Mercedes were achieved under fertilization with either $N_{80}P_{60}K_{60}$ or $N_{120}P_{90}K_{90}$. Under these conditions, seed production and biomass energy accumulation occurred with high plasticity, and overall, the cultivation conditions corresponded to intensive farming systems. This promoted effective realization of the crops' biological potential and efficient use of technological elements, particularly fertilization.

Keywords: yield plasticity and stability, energy output, oil content, oil yield, biofuel.

INTRODUCTION

Brassicaceae crops are highly promising for cultivation in cool climates due to their strong resistance to low temperatures and their ability to produce good yields under such conditions. These traits are particularly important for agricultural production in the Polissia region of Ukraine, where traditional oilseed crops such as sunflower and soybean are unable to achieve high yields. As a result, several species from this family are considered valuable for wider adoption, including rapeseed (*Brassica napus*), cabbage (*Brassica oleracea*), wintercress (*Barbarea vulgaris*), oilseed radish (*Raphanus sativus var. oleifera*), black mustard (*Sinapis* spp.), and typhon (*B. rapa* ssp. *oleifera f. biennis* × (*B. rapa* ssp. *rapifera* × *B. rapa* ssp. *pekinensis*)) (Downey, 1983; Velasco et al., 1998; Sauer and Kramer, 1983).

However, the relatively low productivity of these crops prevents them from serving as effective substitutes for traditional oilseed crops. Therefore, numerous studies have been conducted on various Brassicaceae representatives, such as wintercress (Blume et al., 2017), oilseed radish (Blume and Rakhmetov, 2017), and typhon (Rakhmetov and Rakhmetova, 2015; Rakhmetov, 2007), with the aim of integrating these species into modern agricultural practices. Still, there is a lack of research focused on their fertilization systems, especially in the context of current challenges posed by climate change.

Among all components of agronomic technologies, the most crucial are the primary macronutrients, which play a key role in plant development. For example, nitrogen (N) deficiency can lead to growth retardation and leaf yellowing, as nitrogen is a structural component of amino acids, proteins, and chlorophylls (Van Der Sloot et al., 2022). However, excessive nitrogen application in autumn can increase the risk of winterkill (Webster and Ebdon, 2005), although nitrogen fertilization generally helps reduce yield losses in wheat, barley, and soybean caused by drought (Saravia et al., 2016; Basal and Szabó, 2020). Phosphorus (P) is part of nucleic acids and phospholipids in cell membranes and is involved in energy metabolism (Liu et al., 2015; De Bang et al., 2021). Applying phosphorus fertilizers can help alleviate plant stress (Khan et al., 2023; Xu et al., 2022b), improve cold tolerance, and increase dry matter accumulation (Evans et al., 2016). Potassium (K), acting as an osmolyte, is key to mitigating abiotic stress in plants (Hasanuzzaman et al., 2018). Potassium fertilization enhances photosynthesis and boosts antioxidant enzyme activity (Ma et al., 2019; Qu et al., 2022).

As a result, farmers commonly apply substantial amounts of nitrogen (Zhu and Chen, 2002), as well as potassium and phosphorus fertilizers (Cong et al., 2016; Ren et al., 2016) to ensure high yields under intensive cultivation systems. However, plant response to fertilization depends on both the biological characteristics of the species or variety and seasonal meteorological conditions during the growing period (Ocwa et al., 2023). Therefore, it is essential to study the fertilization response of new species within a multi-year context.

The ecological assessment of Brassicaceae crops has been conducted by researchers in terms of their suitability for cultivation not only in Ukraine in general but also specifically in the Forest-Steppe agroclimatic zone. Thus, the potential of these crops under local agro-soil conditions is considered promising. However, the effectiveness of the agronomic practices under study – in terms of their influence on crop productivity – can be assessed in various ways. Evaluating the ecological components of productivity formation in these crops represents an innovative approach, since growing conditions and technological elements essentially act as controlled ecological factors. These can either broaden or limit the crop's variability under the same cultivation environment (Rakhmetov, 2018; Matsera, 2018).

A traditional method for ecological assessment of agricultural crops is based on yield stability and plasticity, following the Eberhart–Russell methodology. These two traits are expressed through plasticity (b), which is the regression response to changing growing conditions, and stability (W), which is the standard deviation from the regression line (Eberhart and Russell, 1966).

Under experimental conditions where factors supporting productivity are present, crops with low plasticity (b) and low W values indicate that other environmental factors are limiting. In such cases, despite adequate fertilization, the plants utilize other available resources, and we do not observe significant yield increases. Yet, cultivating crops under such conditions becomes economically unviable, as the additional costs – e.g., for fertilizers – are not offset by higher productivity, even in favorable years, due to the shortage of other critical factors (Prysiazhniuk et al., 2025). In contrast, when Brassicaceae crops demonstrate high yield plasticity and low W values, they can achieve high productivity through optimal use of the technological inputs introduced. In such conditions, not only are high yields achieved, but plants also remain resilient to environmental constraints that might otherwise drastically reduce their productivity (Rakhmetov et al., 2008).

Therefore, the aim of our research is to investigate the productivity of winter Brassicaceae crops under different fertilization rates and the influence of agroecological factors during the vegetation periods.

MATERIALS AND METHODS

The research was conducted during 2019–2023 at the Nizhyn Agrotechnical Institute, a separate division of the National University of Life and Environmental Sciences of Ukraine (Chernihiv region). The study focused on the following cultivation technology components:

Brassicaceae family crops and the effects of mineral fertilization.

Wintercress (cv. Oriana), winter rapeseed hybrid Mercedes, and typhon (cv. Orakam) were grown with a row spacing of 15 cm under three fertilization regimes: no fertilizer (control), $N_{80}P_{60}K_{60}$, and $N_{120}P_{90}K_{90}$. This formed a classic full-factorial three-factor field experiment. The area of an elementary plot was 35 m², with an accounting area of 25 m², and the experiment was replicated three times.

Only varieties of Brassicaceae crops officially registered in Ukraine were used in the trials. The typhon variety Orakam was developed at the M. M. Hryshko National Botanical Garden of the NAS of Ukraine and included in the State Register of Plant Varieties of Ukraine in 1998. Wintercress cv. Oriana, also bred by the same institution, was registered in 2003. The winter rapeseed hybrid Mercedes is a mid-season, high-yielding hybrid developed by Lembke, with a yield potential of up to 6.0 t/ha and registered in Ukraine in 2015.

The soil at the research site was podzolic chernozem with a humus content of 3.38–3.76% (elevated), mineral nitrogen (NH_4 + NO_3) levels of 18.6–29.4 mg/kg (medium to elevated), available phosphorus and exchangeable potassium levels of 106.6–120.6 and 50.04–72.2 mg/kg (medium), magnesium content of 243.0–364.5 mg/kg (elevated to high), mobile sulfur of 7.7–10.3 mg/kg (medium to high), and exchangeable calcium of 2225–4100 mg/kg (elevated to very high). Soil pH ranged from 5.7 to 6.5.

The weather and climate conditions during the research years showed deviations from the long-term average values, but this did not hinder the acquisition of objective field data or the growth and development of winter Brassicaceae oilseed crops. The most favorable temperature and moisture conditions were recorded during the 2020/21 growing season, while the least favorable were in 2018/19. The 2021/22 and 2022/23 seasons provided favorable conditions that resulted in above-average yields of winter rapeseed. Overall, the observed changes in weather conditions allowed for a comprehensive evaluation of how the selected agrotechnical factors influenced plant growth and development.

The general cultivation practices for winter Brassicaceae crops in the field trials followed standard approaches for the Right-Bank Forest-Steppe of Ukraine, with the exception of the studied elements. The cultivation technology for typhon was based on that of winter rapeseed, as there is currently no established standard cultivation protocol for typhon in Ukraine. Phosphorus and potassium fertilizers were applied in autumn before sowing. Nitrogen fertilizers were applied both in autumn into the row spacing during sowing (N20) and in spring – via early spring top dressing with ammonium sulfate (40–60 kg/ha a.i.) and urea (20–40 kg/ha a.i.) three weeks later.

Yields were measured using a full-plot harvesting method with a SAMPO-500 breeding combine, followed by recalculation to per-hectare yield and adjustment for seed moisture content.

The trials were conducted according to standard agronomic research methodologies as well as specialized procedures (Prysiazhniuk et al., 2021; Ermantraut et al., 2007).

The calculation of ecological stability and plasticity indicators for winter Brassicaceae crops was performed according to the Eberhart–Russell method using the PTC Mathcad Prime 3.1 software package (Eberhart and Russell, 1966).

RESULTS AND DISCUSSION

The analysis of seed yield in winter crops of the Brassicaceae family showed that the highest yield was recorded in 2021, while the lowest occurred in 2019, which was primarily due to objective environmental factors – namely, air temperature fluctuations and a lack of precipitation. On average across the experiment, the wintercress variety Oriana produced a seed yield of 2.45 t/ha, while the Mercedes winter rapeseed variety demonstrated a productivity level of 4.05 t/ha. In comparison, the typhon variety Orakam had an average yield of 3.64 t/ha across the experiment (Table 1).

Overall, it was found that mineral fertilization contributed to improved seed yield. Specifically, when mineral fertilizer was applied at a rate of $N_{80}P_{60}K_{60}$, the typhon variety Orakam produced 0.44 t/ha more seed compared to the control, and wintercress yield increased by 0.21 t/ha. The application of a higher fertilizer dose ($N_{120}P_{90}K_{90}$) had varied effects among the studied crops due to their biological differences. For instance, the yield increase in wintercress variety Oriana was 0.32 t/ha, in Mercedes winter rapeseed it was 0.55 t/ha, while in typhon variety Orakam it was only 0.12 t/ha.

Table 1. Seed yield and quality of winter Brassicaceae crops, average for 2019–2023

Crop	Fertilization rate, kg/ha	Seed yield, t/ha	Energy output from aboveground biomass, Gcal/ha	Oil content in seed, %	Oil yield from seed, kg/ha
Wintercress (cv. Oriana)	No fertilizer (control)	2.27	64.6	33.4	757
	$N_{80}P_{60}K_{60}$	2.48	70.8	34.0	843
	$N_{120}P_{90}K_{90}$	2.59	74.0	34.2	886
Winter rapeseed (cv. Mercedes)	No fertilizer (control)	3.74	78.8	45.6	1704
	$N_{80}P_{60}K_{60}$	4.12	86.9	45.8	1887
	$N_{120}P_{90}K_{90}$	4.29	90.7	46.0	1973
Typhon (cv. Orakam)	No fertilizer (control)	3.45	79.5	41.2	1421
	$N_{80}P_{60}K_{60}$	3,89	89.2	42.0	1632
	$N_{120}P_{90}K_{90}$	3.57	82.0	42.6	1516
$LSD_{0.05}$		0.14	1.1	1.2	43.0

Thus, among all the studied crops, typhon showed the best seed yield of 3.89 t/ha under the $N_{80}P_{60}K_{60}$ fertilization rate. While both wintercress and rapeseed responded positively to additional fertilization, the yield increases of 0.11 and 0.17 t/ha, respectively, were insufficient to offset the costs of purchasing and applying the additional mineral fertilizer (Figure 1). In fact, only typhon showed a lower yield response under the $N_{120}P_{90}K_{90}$ application, which, according to other researchers, may be explained by its well-developed root system and lower sensitivity to increased mineral nutrition compared to other Brassicaceae crops (Rakhmetov, 2018; Matsera, 2018).

It was also found that the energy yield per unit of total biomass of the typhon variety Orakam averaged 4179 kcal/kg across the experiment. Weather conditions had little influence on this indicator: in 2020, the energy equivalent of biomass was 4174 kcal/kg, while during the 2019 and 2021 growing seasons, the average was 4182 kcal/kg. Therefore, although the energy value of typhon aboveground biomass varied from year to year, no significant fluctuations were observed.

Among the other studied crops, the lowest energy output was recorded for the biomass of Mercedes winter rapeseed – 3843 kcal/kg – while wintercress variety Oriana showed a higher energy density at 4090 kcal/kg. Comparing these values suggests that fertilization had a minimal impact on this trait. In other words, plants inherently develop a certain level of energy efficiency, and the differences observed were minimal and likely due to biological variation and experimental error.

The energy output from aboveground biomass is a cumulative characteristic, combining total biomass yield per unit area and the caloric value of the biomass. Accordingly, the lowest average energy yield from biomass was observed in wintercress Oriana – 64.6 Gcal/ha – while Mercedes winter rapeseed showed higher values at 78.8 Gcal/ha. Thus, even with higher caloric content per biomass unit, total accumulation remains critical, and wintercress generated a lower overall energy yield.

Since fertilization contributes significantly to biomass accumulation, it plays a crucial role in the total energy accumulation of Brassicaceae crops. It was determined that when applying fertilizer at a rate of $N_{80}P_{60}K_{60}$, the total energy yield ranged from 70.8 to 89.2 Gcal/ha, and at $N_{120}P_{90}K_{90}$, from 74.0 to 90.7 Gcal/ha.

The lowest average oil content in seeds was recorded for the wintercress variety Oriana – 33.9%, while the highest was in Mercedes winter rapeseed – 45.8%. Typhon Orakam, on average, had an oil content of 41.9%. This indicator also varied across the years. For typhon Orakam, the poorest result was observed in 2019, with an oil content of 41.8%, while the most favorable growing seasons were 2020–2021, during which the average oil content reached 42.7%.

Similar trends in oil content changes were noted for other Brassicaceae crops – wintercress Oriana and rapeseed Mercedes – indicating that the 2020–2021 growing seasons provided the best conditions for effective synthesis and accumulation of oil in the seeds, while the 2018–2019 seasons were less favorable.

It was found that fertilization plays a significant role in forming high oil content in the seeds of Brassicaceae crops. Even under conditions of high natural soil fertility, plants expend considerable

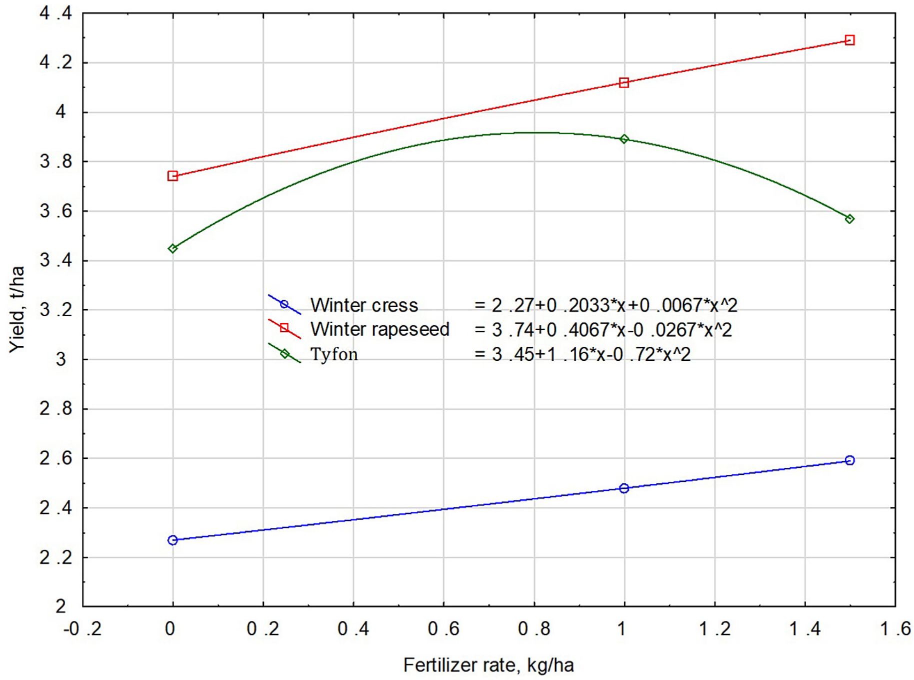

Figure 1. Dependency of Brassicaceae crop yield on mineral fertilizer application rates (1.0 – $N_{80}P_{60}K_{60}$, 1.5 – $N_{120}P_{90}K_{90}$)

energy to search for and assimilate mineral nutrients, whereas mineral fertilizers provide these nutrients in an accessible form with lower energy expenditure. As a result, the oil content under fertilization with $N_{80}P_{60}K_{60}$ ranged from 34.0% to 45.8%, and under the $N_{120}P_{90}K_{90}$ regime, it was between 34.2% and 46.0%. Similar results have been reported by other researchers, with the total oil yield increasing with higher fertilizer application rates, and the highest value observed under $N_{240}P_{120}K_{240}$ (Mazur and Matsera, 2019).

It was also found that the lowest average oil yield was recorded for wintercress Oriana – 828.6kg/ha, while the highest yield was in Mercedes winter rapeseed – 1854.8 kg/ha. Typhon Orakam provided an average oil yield of 1523.0kg/ha throughout the study. Fertilization plays an important role not only in achieving high oil content in the seeds of Brassicaceae crops but also in obtaining a substantial overall oil yield. For example, under $N_{80}P_{60}K_{60}$ fertilization, oil yield varied across crops from 843 to 1887 kg/ha, while under N120P90K90, it ranged from 886 to 1973 kg/ha.

An assessment was also carried out for the stability coefficient (b) and plasticity (W) of seed yield and energy output from aboveground biomass of Brassicaceae crops (Table 2).

When analyzing the stability of seed yield formation and energy output from aboveground biomass, high plasticity was mostly characteristic of Brassicaceae crop cultivation variants fertilized with $N_{80}P_{60}K_{60}$ and $N_{120}P_{90}K_{90}$.

Additionally, a comprehensive assessment of the environmental characteristics of the conditions under which seed yield and energy output from the aboveground biomass of Brassicaceae crops were formed was conducted (Table 3).

When analyzing seed yield indicators comprehensively, the most favorable conditions for realizing biological potential were observed in the crops of the winter rapeseed hybrid Mercedes and the typhon variety Orakam under the application of mineral fertilizers at rates of $N_{80}P_{60}K_{60}$ or $N_{120}P_{90}K_{90}$. Under these conditions, seed yield formation occurred with a high level of plasticity, and in general, the conditions matched the requirements of intensive cultivation systems, supporting the effective expression of the crops' biological potential and efficient use of technological elements, particularly fertilization. The wintercress variety Oriana also demonstrated favorable conditions for expressing its biological potential when fertilized with $N_{80}P_{60}K_{60}$.

In terms of energy output from the aboveground biomass – evaluated from the perspective of its suitability for bioenergy processing – he plants

Table 2. Stability (b) and plasticity (W) of seed yield and energy output from aboveground biomass of Brassicaceae crops, average for 2019–2023

Crop	Fertilization rate, kg/ha	Seed yield		Energy output from aboveground biomass	
		b	W	b	W
Wintercress (cv. Oriana)	No fertilizer (control)	0.96	1.38×10^4	1.17	7.12×10^6
	$N_{80}P_{60}K_{60}$	1.05	1.29×10^4	1.07	6.97×10^6
	$N_{120}P_{90}K_{90}$	0.98	1.22×10^4	0.96	6.80×10^6
Winter rapeseed (cv. Mercedes)	No fertilizer (control)	0.92	1.25×10^4	0.84	6.85×10^6
	$N_{80}P_{60}K_{60}$	1.20	1.29×10^4	1.18	6.89×10^6
	$N_{120}P_{90}K_{90}$	1.24	1.27×10^4	1.23	6.84×10^6
Typhon (cv. Orakam)	No fertilizer (control)	0.80	1.29×10^4	0.82	6.86×10^6
	$N_{80}P_{60}K_{60}$	1.26	1.28×10^4	1.23	6.86×10^6
	$N_{120}P_{90}K_{90}$	1.34	1.25×10^4	1.33	6.68×10^6

Table 3. Environmental characteristics of the conditions for seed yield formation and energy output from aboveground biomass of Brassicaceae crops, average for 2019–2023

Crop	Fertilization rate, kg/ha	Seed yield	Energy output from aboveground biomass
Wintercress (cv. Oriana)	No fertilizer (control)	Low plasticity	High plasticity
	$N_{80}P_{60}K_{60}$	High plasticity, intensive conditions	High plasticity, intensive conditions
	$N_{120}P_{90}K_{90}$	High plasticity	High plasticity
Winter rapeseed (cv. Mercedes)	No fertilizer (control)	Low plasticity, limiting factors	Low plasticity
	$N_{80}P_{60}K_{60}$	High plasticity, intensive conditions	High plasticity, intensive conditions
	$N_{120}P_{90}K_{90}$	High plasticity, intensive conditions	High plasticity, intensive conditions
Typhon (cv. Orakam)	No fertilizer (control)	Low plasticity, limiting factors	Low plasticity
	$N_{80}P_{60}K_{60}$	High plasticity, intensive conditions	High plasticity, intensive conditions
	$N_{120}P_{90}K_{90}$	High plasticity, intensive conditions	High plasticity, intensive conditions

of the typhon variety Orakam and the winter rapeseed hybrid Mercedes also showed strong development under the application of N80P60K60 or N120P90K90. With these cultivation practices, biomass accumulation and the overall energy yield from the aboveground mass were characterized by high plasticity and aligned well with the parameters of intensive crop production.

CONCLUSIONS

Among all the studied Brassicaceae crops, it was typhon that showed the highest seed yield (3.89 t/ha) under fertilization at the rate of $N_{80}P_{60}K_{60}$. While both wintercress and rapeseed responded positively to additional fertilization, their respective yield increases of 0.11 and 0.17 t/ha did not justify the costs associated with purchasing and applying additional mineral fertilizers. Only typhon demonstrated a lower yield gain under the higher $N_{120}P_{90}K_{90}$ rate compared to the $N_{80}P_{60}K_{60}$ rate.

Key indicators such as energy output from aboveground biomass and oil yield from Brassicaceae seeds were significantly influenced by fertilization regimes. As fertilizer intensity increased from $N_{80}P_{60}K_{60}$ to $N_{120}P_{90}K_{90}$, both energy yield and oil output also rose. However, the efficiency of increasing fertilizer doses should be assessed through a separate economic analysis.

The most favorable conditions for realizing the biological potential and achieving optimal seed yield and total aboveground energy output for the typhon variety Orakam and the winter rapeseed hybrid Mercedes were observed under mineral fertilization at $N_{80}P_{60}K_{60}$ or $N_{120}P_{90}K_{90}$. Under these conditions, seed formation and biomass energy accumulation occurred with high plasticity, and the overall environment reflected intensive cultivation systems – promoting effective biological potential expression and efficient use of technological elements, particularly fertilization.

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