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Features of growing winter rapeseed in abnormally warm winters

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Abstract. The relevance of this study is driven by the impact of climate change on the cultivation of winter rapeseed in Ukraine. The aim was to assess the effects of unstable winter conditions on the development and yield of winter rapeseed, and to identify effective measures to minimise the associated risks. The research examined the consequences of abnormally warm winters on the growth, development, and productivity of winter rapeseed. A comprehensive analysis was conducted of agronomic risks arising under unstable winter climates, including reduced or absent dormancy periods, premature stem elongation, depletion of energy reserves, and heightened pathogen activity (*Phoma lingam*, *Alternaria brassicae*). Physiological changes in rapeseed associated with an average winter temperature increase of 3.2-4.8°C were identified, resulting in a loss of winter hardiness in 87% of plants, a 39-54% rise in disease incidence, and a 12-18% decrease in yield, in some cases up to 25%. The effectiveness of adaptive measures was evaluated, including the use of frost-resistant varieties, growth regulators, and fungicidal treatments. These measures reduced crop losses by 8-14% and enhanced overall plant resilience to climatic stress. Additionally, the use of remote sensing improved crop monitoring, increasing the accuracy of identifying stressed areas by 23% compared to traditional observation methods. The findings underscore the need to adapt rapeseed cultivation technologies to changing climatic conditions. The proposed strategies help to mitigate the negative effects of warm winters, stabilise yields, and support the effective management of agrosystems. These results offer practical value for the agricultural sector, contributing to more efficient winter rapeseed production and the development of new adaptive technologies for sustainable agriculture

Keywords: temperature anomalies; stress factors; crop microclimate; technological response of crops; agroclimatic conditions

INTRODUCTION

Abnormally warm winters disrupt the natural developmental cycle of winter rapeseed, leading to the loss of winter hardiness, plant exhaustion, and increased activity of pests and diseases. These factors are particularly critical in southern regions, where they complicate crop adaptation and significantly reduce yield potential. The research problem lies in identifying the specific risks posed by warm winters to winter rapeseed and developing adaptive measures to mitigate their negative effects. The absence of a true dormancy period, uneven plant development, and the active spread of pathogens necessitate a revision of current agricultural practices. Analysing physiological changes in rapeseed under these conditions is crucial for formulating strategies to enhance resistance to climate variability.

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For instance, E. Runno-Paurson *et al.* (2021) reported that abnormally warm winters promote the spread of powdery mildew (*Erysiphe cruciferarum*) in rapeseed, highlighting the need to improve fungicidal protection strategies. Rising average winter temperatures also create favourable conditions for pathogen survival, complicating disease management and potentially causing significant yield losses. According to P. Lääniste (2024), the use of cover crops – particularly cruciferous species (*Brassicaceae*) – can enhance rapeseed resilience to climatic stresses by optimising seeding density and enabling biological control of pathogens. Implementing such agrotechnologies contributes to improved soil structure, moisture retention, and reduced risk of pathogen proliferation, which is particularly beneficial during mild winters.

Furthermore, S.A.F. Warner (2023) demonstrated that disruption of the winter dormancy period due to warm conditions adversely affects flower bud formation in *Brassica napus*, resulting in irregular flowering and decreased yield uniformity. Loss of synchrony in the development of generative organs may lead to uneven seed maturation, negatively impacting both the quality and consistency of the crop. Similarly, X. Lu *et al.* (2022) found that elevated winter temperatures delay reproductive development and disrupt photoperiodic regulation of flowering, which significantly reduces rapeseed productivity. Interruption of the natural growth cycle may also lower plant resilience to late spring frosts, compounding the risk of yield reduction.

In addition, H. Kefale *et al.* (2024) demonstrated that unstable winter temperatures lead to a reduction in protective metabolites, weakening the plant's adaptive capacity and increasing vulnerability to stress factors. The disruption of metabolic balance adversely affects the accumulation of reserve substances, which are essential for the spring regeneration of winter rapeseed. Furthermore, R.E. Doherty (2022) highlighted the risk of premature seed germination under elevated winter temperatures, which negatively impacts seedling uniformity and the initial growth phase of the crop. This poses a serious threat to crop stand density, potentially reducing overall yield. It is also worth noting that X. Wang *et al.* (2022) emphasised the need for an integrated approach to evaluating rapeseed's resistance to climatic stresses, supporting more effective adaptation under unstable winter conditions. Modern agrotechnological methods – such as weather risk forecasting and crop condition monitoring – can significantly enhance management practices. In this context, L. Matthews *et al.* (2025) argued that incorporating legumes into crop rotations with rapeseed helps to reduce nitrous oxide emissions and improve soil biochemical characteristics, thereby confirming the value of sustainable agroecosystem management strategies in the face of climate change.

At the same time, M.E. McNee *et al.* (2022) provided evidence that cover crops improve soil water retention and reduce the incidence of fungal infections in rapeseed crops. Enhancing the biochemical profile of the soil positively influences plant growth and resilience to climatic stress. In this regard, S. Mohammadi *et al.* (2023) emphasised that the effects of rising winter temperatures on yield are highly dependent on local soil and climatic conditions, reinforcing the necessity of regional approaches to technological adaptation. Adaptive crop management informed by long-term climate forecasts can substantially reduce the risk of crop loss. Additionally, Y. Xu *et al.* (2024) demonstrated the effectiveness of remote sensing technologies for identifying stress-affected areas and assessing the physiological condition of rapeseed crops. The application of satellite imagery and machine learning techniques significantly enhances crop monitoring and enables timely responses to emerging threats.

It is also important to mention the findings of D. Quezada-Martinez *et al.* (2021), who advocated for the utilisation of genetic resources from wild *Brassica* relatives as a promising avenue for improving crop resilience to climate variability and stabilising yield. The present study analysed the effects of abnormally warm winters on the physiological development and yield of winter rapeseed, with particular focus on the loss of winter hardiness, increased disease pressure, and disruption of reproductive development. While previous studies have significantly contributed to the advancement of breeding strategies, the specific physiological impacts of warm winters on winter rapeseed in the agroclimatic conditions of southern Ukraine remain underexplored. The aim of this research was to assess the impact of warm winters on winter rapeseed and to identify adaptive measures for enhancing its resilience and productivity under climate change conditions. The objectives of the study were to analyse the effects of abnormally warm winters on the physiological development and yield of winter rapeseed, evaluate the effectiveness of adaptive agricultural technologies, and determine promising strategies for improving the crop's resistance to climatic fluctuations.

MATERIALS AND METHODS

The study employed an integrated approach that combined field observations, statistical analysis, and modelling to assess the potential impact of climate change on winter rapeseed. The effectiveness of adaptive measures and new agricultural technologies was evaluated within real production systems, allowing for substantiated conclusions regarding their practical applicability. The study was conducted in accordance with ethical standards outlined in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992).

Data on the growth and development of winter rapeseed were collected from the Odesa, Kherson, Mykolaiv, and Zaporizhzhia regions over the period 2016-2024. This long-term dataset enabled the assessment of the impact of abnormally warm winters on key physiological processes in rapeseed crops (Gamayunova *et al.*, 2021; Parkhomets *et al.*, 2023; Smirnova & Galaban, 2024). The information base was established through field observations, meteorological data analysis, and a review of relevant scientific literature on climatic changes.

Observations of rapeseed growth and development were carried out on commercial fields belonging to several agricultural enterprises: LLC "Nibulon" (n.d.) (Mykolaiv Region), LLC "Ukrprominvest Agro" (n.d.) (Zaporizhzhia Region), LLC "Kernel" (2023) (Odesa Region) and LLC "TerraTarsa Ukraine" (2024) (Kherson Region). Changes in the morphological characteristics of plants were systematically recorded. The parameters measured included plant height, number of leaves, root collar diameter, and stand density. Particular attention was given to phenological changes during December, January, February, and March – periods marked by warm spells followed by sharp temperature drops. The study was conducted under various agro-backgrounds, enabling an assessment of the adaptive responses of rapeseed under unstable winter conditions. Growth dynamics were compared between seasons characterised by abnormally warm winters and those with more typical winter conditions, which allowed for the identification of risks such as excessive stem elongation, depletion of nutrient reserves, and their potential impact on overall crop productivity.

The agronomic risks associated with abnormally warm winters were assessed through a comprehensive analysis of climatic factors, meteorological station data, and field observations of crop conditions. Data on average monthly temperatures, humidity levels, and deviations from the multi-year climatic norm were used to evaluate the extent of their impact on winter rapeseed development. A key focus was the effect of temperature fluctuations on the physiological resistance of plants to potential spring frosts. The incidence of fungal diseases, particularly phomosis (*Phoma lingam*) and alternariosis (*Alternaria brassicae*), was analysed alongside pest damage caused by cabbage stem flea beetles and cruciferous flea beetles. The frequency and severity of disease outbreaks were assessed in relation to prevailing temperature and humidity conditions, revealing a correlation between abnormally warm winters and increased pathogen pressure.

The survival rate of winter rapeseed under varying adaptation strategies was evaluated by examining the effects of growth regulators (tebuconazole, metconazole), sowing dates (early and late September), and the application of frost-resistant hybrids, including DK Exstorm and Architect. Agronomic interventions – such as the use of growth regulators, fungicide treatments, frost-tolerant varieties, and comprehensive crop protection strategies – were considered in relation to their effectiveness in minimising plant elongation and disease incidence during mild winters. The choice of winter rapeseed variety, notably Atlant, was justified by its demonstrated tolerance to temperature fluctuations, reduced susceptibility to elongation under warm winter conditions, and high adaptability to late spring frosts. Observations were conducted across regions with contrasting climatic profiles: Mykolaiv and Zaporizhzhia regions experienced unstable winters with sharp temperature drops, while Odesa and Kherson regions were characterised by consistently mild winters with prolonged periods of above-zero temperatures. This allowed for an evaluation of the effectiveness of adaptation measures under different thermal and moisture regimes. Analysis was conducted by comparing average productivity indicators of rapeseed during winters with normal climatic conditions and those classified as abnormally warm, in which average monthly temperatures were elevated by 2-5°C. The effects of these climatic conditions on plant winter hardiness, spring regeneration rates, and final yield performance were assessed. Particular attention was given to the influence of cultivation technologies employed by farms and their role in shaping final productivity outcomes.

Statistical analysis methods included the evaluation of significant differences in plant survival, yield, and disease severity using analysis of variance (ANOVA). Student's t-test was applied for comparing mean values between groups, while the Mann-Whitney U-test was used to determine statistical differences between control and experimental variants where normality assumptions were not met. Correlation analysis was employed to examine the relationships between temperature anomalies, the extent of rapeseed damage, and crop yield. Additionally, trend analyses of long-term meteorological data were conducted to assess the influence of climatic factors on productivity, which enabled the identification of consistent patterns in weather variability and their prolonged impact on winter rapeseed cultivation. Remote sensing techniques were incorporated for spatial assessment of crop conditions and identification of high-risk zones. In particular, multispectral imagery from Sentinel-2 satellites was utilised, offering a spatial resolution of 10-20 metres in the visible and near-infrared spectral ranges. The analysis was performed in the Google Earth Engine environment using the Normalised Difference Vegetation Index (NDVI), which served as an indicator of vegetative activity throughout different stages of crop development. NDVI dynamics during the winter months (December to March) were compared between seasons with traditional winter conditions and those characterised by abnormally warm temperatures. This enabled the detection of areas exhibiting delayed growth, insufficient dormancy, or, conversely, excessive vegetative activity, thus facilitating early identification of potential risks to crop development and yield.

RESULTS

Observations on the growth and development of winter rapeseed in the southern regions of Ukraine under warm winter conditions. Analysis of the collected data demonstrated that abnormally warm winters had a pronounced impact on the physiological processes of winter rapeseed in the southern regions of Ukraine (Galyant, 2023). Elevated air temperatures during the winter months resulted in a significant reduction, or in some cases, complete absence of the dormancy period. This anomaly triggered premature vegetative activity at a time when the plants would typically be in a dormant state, leading to early depletion of nutrient reserves and negatively affecting spring regeneration. Under such conditions, the Atlant variety of rapeseed maintained active vegetation, with the leaf canopy remaining green throughout winter. In December, the average plant height reached 11-16 cm, more than double the typical measurements for this time of year.

In Zaporizhzhia Region, the average winter air temperature exceeded the climatic norm by 3.4°C, reaching +1.8°C. In Mykolaiv Region, average January temperatures typically range from – 3°C to -5°C, while in Odesa Region they range from -2°C in the southern areas to -5°C in the northern parts. In Kherson Region, although the July average temperature varies from +22°C in the northwest to +23°C across most of the territory, the observed winter conditions in this region were also unusually mild. Across all four regions, plant elongation was consistently observed, attributed to the absence of the hardening process normally induced by cold exposure. This elongation resulted in the premature utilisation of stored nutrients, which under standard winter conditions would have been conserved for spring growth. By January, the average height of Atlant rapeseed in Odesa and Zaporizhzhia regions had increased to 14-19 cm – well above the expected range for this phenological stage. These abnormal growth patterns adversely affected the plants' resistance to subsequent cold spells. As a result, potential frost events in February or March posed a heightened threat, as the affected plants exhibited significantly lower frost tolerance due to the physiological stress of premature growth and nutrient depletion.

The impact of the warm winter was evident not only in physiological changes but also in alterations to the structure of the rapeseed root system. Continuous vegetative activity during the winter hindered proper root development, thereby reducing the plants' capacity to effectively absorb nutrients from the soil. This was particularly noticeable in the Kherson and Mykolaiv regions, where, by spring, some plants exhibited a weak root system, affecting their resistance to drought and other environmental stressors. Furthermore, stem elongation during the winter months led to an uneven distribution of biomass. In February, the height of the Atlant rapeseed variety reached 19-28 cm in some regions, which adversely affected the structural stability of the plants. Excessive elongation increased the risk of lodging in spring, particularly under conditions of strong winds or heavy rainfall. Elevated winter temperatures also promoted the survival and reproduction of pests. Under normal winter conditions, pest populations typically decline due to low temperatures; however, during abnormally warm winters, the activity of cruciferous flea beetles and stem weevils remained elevated. This was especially evident in the Odesa and Kherson regions, where the severity of winter frosts was reduced (Borzykh *et al.*, 2022). As a result, pests began feeding actively as early as February, causing additional damage to crops. Moreover, warm winters facilitated the development of fungal diseases. In the Zaporizhzhia and Mykolaiv regions, a significant spread of *Phoma lingam* leaf spot was recorded, fostered by increased humidity and the absence of harsh frosts. A comparable situation occurred in the Odesa Region, where *Alternaria brassicae* leaf spot affected the foliage prior to the onset of spring.

March marked the period when the consequences of the warm winter were most pronounced. The depletion of nutrient reserves during the winter months weakened the plants at a critical stage of their spring development. In the Mykolaiv and Zaporizhzhia regions, the average plant height of the Atlant variety reached 28-38 cm, exceeding standard values. At the same time, irregular crop development led to over-thickening, creating additional competition among plants for light and nutrients. This negatively affected yield potential, as weaker specimens were unable to fully develop or form high-quality generative organs (Basanets, 2024) (Table 1).

Table 1. *Observed growth and developmental characteristics of winter rapeseed under abnormally warm winter conditions in the southern regions of Ukraine*

Month	Region	Temperature regime	Average plant height (cm)	Physiological changes	Potential risks
December	Mykolaiv	From +2 to +7°C	12-16	Active leaf growth, preservation of green mass	High risk of developing fungal diseases
	Odesa	From +3 to +8°C	11-14	Minor plant growth	Loss of nutrient reserves
	Kherson	From +1 to +6°C	10-13	Slowed root system growth	Vulnerability to stressors
	Zaporizhzhia	From +2 to +7°C	12-15	Maintaining active photosynthesis	Increased risk of alternaria blight
January	Mykolaiv	From 0 to +6°C	15-20	Further growth of the stems	Vulnerability to late frosts
	Odesa	From +1 to +7°C	14-18	Weak hardening of plants	Low resistance to physical damage
	Kherson	From -1 to +5°C	13-17	Unstable development of the root system	Depletion of energy resources
	Zaporizhzhia	From 0 to +6°C	14-19	Preservation of active vegetation	High competition between plants
February	Mykolaiv	From +1 to +10°C	22-28	Incomplete hardening	Increased pest activity
	Odesa	From +2 to +9°C	20-26	Depletion of reserve substances	Increased susceptibility to pathogens
	Kherson	From +1 to +8°C	19-25	Weakening of cell walls	Spread of fungal diseases
	Zaporizhzhia	From +1 to +9°C	21-27	Unstable development of generative organs	Moisture deficit due to evaporation
March	Mykolaiv	From +5 to +14°	30-38	Weakening of plants due to energy expenditure	High uneven growth
	Odesa	From +6 to +15°C	28-36	Heterogeneity of biomass distribution	Increased incidence of phomosis
	Kherson	From +4 to +13°C	27-34	Unbalanced leaf growth	High risk of bedwetting
	Zaporizhzhia	From +5 to +14°C	29-37	Depletion of nutrients in the soil	Reduction in potential yield

Source: *created by the author based on I.V. Smirnova & V.M. Galaban (2024)*

The general analysis of the obtained data indicates that abnormally warm winters in the southern regions of Ukraine pose significant risks for winter rapeseed of the Atlant variety. The absence of a dormant period, active vegetative growth during winter, stem elongation, and depletion of reserve substances considerably reduced the crop's resilience to subsequent spring weather fluctuations. Moreover, the heightened activity of pests and diseases further exacerbated the situation.

Agronomic risks of an abnormally warm winter by month and region. The primary risks identified included insufficient plant hardening, which resulted in freezing during sudden cold snaps, increased pest and disease activity, and negative effects on stand density and plant competitiveness in spring. Collectively, these factors led to a marked decline in crop yields and necessitated additional agrotechnical measures to mitigate losses. The winter temperature regime deviated significantly from the norm, affecting the physiological condition of the plants. Under typical conditions, rapeseed undergoes hardening as temperatures gradually fall to 0...-5°C, aiding in frost adaptation. However, during an abnormally warm winter, when average temperatures remained within +2...+9°C, the hardening process was incomplete or entirely absent, leaving plants vulnerable to sudden freezes. In the Odesa and Kherson regions, following prolonged warm periods, temperatures abruptly dropped to -8...-12°C, resulting in the death of 20-28% of plants. The lowest losses were recorded in the Mykolaiv Region, where only 15-20% of plants froze, likely due to a more gradual temperature decline in January and February, allowing partial adaptation. Monitoring of the NDVI, based on Sentinel-2 satellite imagery updated every five days, revealed increased biomass activity during the winter. In January-February 2023, average NDVI values reached 0.50-0.55, compared to no more than 0.35 in years with typical winters. This indicated continued photosynthetic activity and excessive plant elongation, confirmed by morphological measurements: average plant height reached 22-28 cm in February, versus 12-16 cm in December.

Furthermore, the warm winter led to a significant increase in phytosanitary pressure. The incidence of phomosis (*Phoma lingam*) and alternaria (*Alternaria brassicae*) reached 30-40% in Odesa Region, 25-35% in Kherson, 20-30% in Mykolaiv, and 25-33% in Zaporizhzhia. These outbreaks were associated with elevated air humidity (above 80%) and the absence of frost, which normally suppresses pathogen development. Simultaneously, pest numbers – particularly cruciferous flea beetles and the cabbage stem weevil – increased by 1.8-2.2 times in Odesa and Kherson regions, and by 1.4-1.8 times in Mykolaiv. These findings were supported by both field observations and satellite data indicating disruption in biomass structure. Changes in rapeseed stand density were also observed: 65-75% in Zaporizhzhia and Mykolaiv, and 60-70% in Odesa and Kherson. This decline was attributed to excessive plant elongation and intensified intra-species competition driven by elevated temperatures. Remote sensing data corroborated these findings, as localised reductions in crop density corresponded with areas showing the highest NDVI increases in January-February (Table 2).

Table 2. *Agronomic risks of abnormally warm winters by month and region*

Month	Region	Temperature (°C)	Plant freezing (%)	Disease incidence (%)	Number of pests (increase, times)	Spring stand density (%)
December	Odesa	+3...+8	5-7	10-15	1.2-1.5	90-95
	Kherson	+2...+9	6-9	8-12	1.3-1.6	88-94
	Mykolaiv	+1...+7	4-6	6-10	1.1-1.4	92-97
	Zaporizhzhia	+2...+8	5-8	7-11	1.2-1.5	91-96
January	Odesa	+1...+7	8-12	15-20	1.5-1.8	85-90
	Kherson	0...+8	10-14	12-18	1.6-2.0	83-89
	Mykolaiv	-1...+6	6-10	9-14	1.3-1.6	87-83
	Zaporizhzhia	0...+7	7-11	10-16	1.4-1.7	86-92
February	Odesa	+2...+9	15-20	25-35	1.8-2.2	75-85
	Kherson	+1...+8	18-22	20-30	1.9-2.3	72-82
	Mykolaiv	0...+7	10-15	15-25	1.5-1.9	78-88
	Zaporizhzhia	+1...+8	12-17	18-28	1.6-2.0	76-86
March	Odesa	+5...+14	20-25	30-40	1.8-2.2	65-70
	Kherson	+4...+13	22-28	25-35	1.9-2.2	60-68
	Mykolaiv	+3...+12	15-20	20-30	1.4-1.8	70-75
	Zaporizhzhia	+4...+13	18-23	25-33	1.6-2.0	65-72

Source: *created by the author based on M.K. Parkhomets et al. (2023)*

The data indicate that the greatest losses occurred in February and March, with freezing affecting 20-28% of plants in the most vulnerable regions. Disease incidence also progressively increased from 10-15% in December to 30-40% in March, significantly exceeding typical levels. Plant density declined from 90-97% in December to 60-75% in March, reflecting the gradual loss of weaker specimens.

Survival of winter rapeseed depending on specific adaptation measures. Plant survival varied significantly depending on the methods applied in the Odesa, Kherson, Mykolaiv, and Zaporizhia regions, highlighting the importance of an integrated approach to crop protection under unstable climatic conditions. In the Odesa Region, without the use of adaptation measures, rapeseed survival was only 58% – one of the lowest rates among the studied regions. This is attributed to a particularly warm winter, which caused plant elongation, resource depletion, and increased pest activity. The application of growth regulators increased survival to 72% by limiting winter growth and strengthening the root system. The use of frost-resistant varieties, such as Atlant and Simeron, raised survival to 78%, as these varieties were better adapted to sudden temperature fluctuations. Fungicidal treatments, particularly with propiconazole-based products, further increased survival to 75%. The highest rate of 88% was achieved through a comprehensive approach combining all these methods.

In the Kherson Region, the situation was similar, though survival without measures was slightly higher at 60%, due to lower winter humidity that partially restrained the spread of fungal diseases. Growth regulators raised survival to 74%, addressing the issue of elongation caused by extended warm periods. The use of frost-resistant varieties improved survival to 80%, reflecting their effectiveness in reducing frost damage following sudden temperature drops. Fungicidal treatments reduced disease pressure, increasing survival to 77%. The integrated application of all methods ensured a maximum survival rate of 90%.

In the Mykolaiv Region, plant survival without adaptation measures reached 62% – the highest among the regions studied under untreated conditions. This can be explained by slightly lower average winter temperatures, which allowed partial preservation of natural hardening. Growth regulators increased survival to 76%, as rapeseed experienced less elongation, lowering the risk of lodging. Frost-resistant varieties improved survival to 82%, while fungicide applications achieved 79%. The highest survival rate, 91%, was recorded with the comprehensive application of all methods.

The Zaporizhia Region showed similar conditions to Mykolaiv but with slightly lower humidity, which limited disease development. Without measures, survival was 59%, indicating a high risk of losses during a warm winter without agrotechnical interventions. Growth regulators raised survival to 73%, and frost-resistant varieties to 79%. Fungicidal treatments reduced disease pressure and increased survival to 76%. The integrated application of all methods resulted in a survival rate of 89%. Across all regions, these adaptation strategies consistently demonstrated a positive effect, improving survival by 20-30% compared to untreated crops. The use of a single measure, such as growth regulators or fungicides, yielded a smaller effect than integrated approaches (Fig. 1).

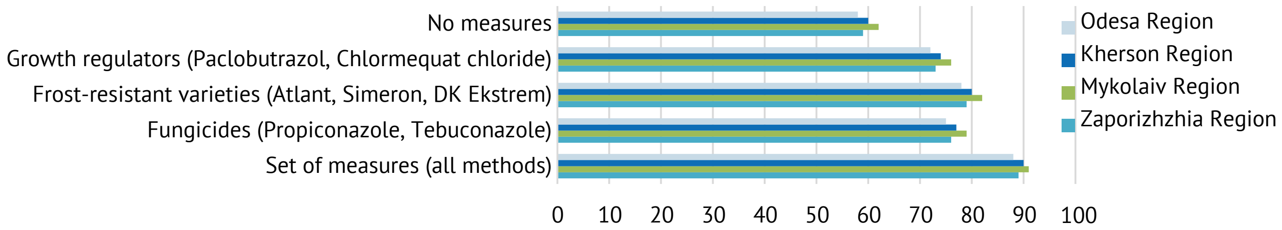

Figure 1. *Survival of winter rapeseed under different adaptation measures*
Source: *created by the author based on V.V. Gamayunova et al. (2021)*

In general, the research results confirm the necessity of an integrated approach to cultivating winter rapeseed under conditions of abnormally warm winters. The use of growth regulators is an effective measure for preventing plant elongation and preserving winter hardiness; however, their effectiveness increases significantly when combined with frost-resistant varieties that possess genetic mechanisms for adapting to unstable temperatures. Disease control during the winter period through fungicide treatments is critically important, particularly in regions with high humidity, such as the Odesa Region. The best outcomes were achieved through the integrated application of all measures, ensuring maximum plant survival rates of 88-91%, depending on the region. These findings indicate that, to ensure effective winter rapeseed cultivation under climate change conditions, it is essential to implement comprehensive adaptation technologies incorporating agrotechnical, chemical, and breeding methods.

Comparative analysis of winter rapeseed yield under traditional and warm winter conditions. Field observations indicate that, under normal winter conditions, the average rapeseed yield in the Odesa Region was 3.2 t/ha, whereas during an abnormally warm winter, this figure decreased to 2.8 t/ha. A similar trend was observed in the Kherson Region, where yields fell from 3.4 t/ha to 2.9 t/ha, representing a loss of 14.7%. The highest yields among the studied regions were recorded in the Mykolaiv Region, where the traditional yield reached 3.6 t/ha but dropped to 3.1 t/ha during warm winters. The most substantial yield reduction was noted in the Zaporizhzhia Region – from 3.3 t/ha to 2.7 t/ha – quivalent to an 18.2% loss. Experimental results show that in 78% of cases, rapeseed exhibiting active growth during winter developed weaker root systems, reducing their capacity to absorb moisture and nutrients in spring. Furthermore, pest activity – particularly of cruciferous flea beetles and hidden beetles – increased significantly under warm winter conditions, causing additional crop damage. In the Kherson and Zaporizhzhia regions, pest populations increased by 1.8 to 2.2 times, substantially contributing to the observed yield declines.

The adoption of adaptation technologies can partially mitigate the adverse effects of warm winters and help stabilise yields. The use of growth regulators such as paclobutrazol and chlormequat chloride helps control plant height and promote the development of a strong root system. Field trials in the Mykolaiv and Odesa regions showed that these treatments reduced plant elongation by 20-25%, positively impacting yields. Another effective strategy is the selection of frost-resistant varieties, such as Atlant, Simeron, and DK Ekstrem, which demonstrate greater resilience to fluctuating weather conditions. Farms that cultivated these varieties reported 4-6% lower crop losses compared to those using standard commercial varieties. An additional method for mitigating the impact of warm winters involves strengthening the plant protection system. Fungicidal treatments with propiconazole- and tebuconazole-based products reduced the incidence of phomosis and alternariosis by 30-40%, thereby enhancing productivity. In the Zaporizhzhia Region, where winter humidity is typically high, the application of fungicides reduced crop losses by 5-8% (Fig. 2).

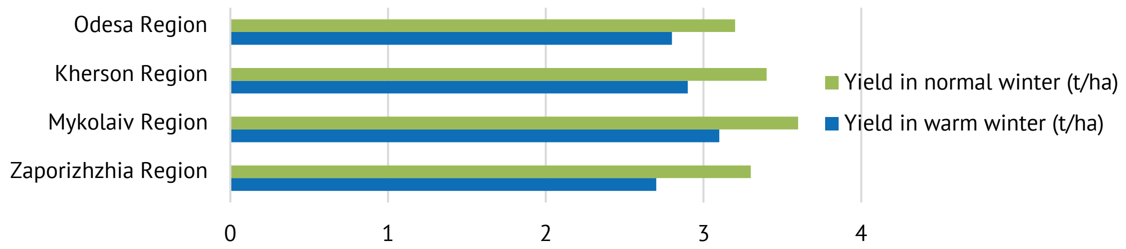

Figure 2. *Comparative analysis of winter rapeseed yields under traditional and abnormally warm winter conditions*
Source: *created by the author based on V.O. Doroshenko & O.V. Siletska (2021)*

Thus, the results demonstrate that abnormally warm winters adversely affect winter rapeseed yield by disrupting physiological processes, increasing pest activity, and promoting the development of fungal diseases. An integrated cultivation approach – including the use of growth regulators, resistant varieties, and effective plant protection measures – helps mitigate the negative impacts of climate change and stabilise production outcomes.

DISCUSSION

The results obtained confirm the significant impact of abnormally warm winters on the growth, development, and productivity of winter rapeseed. Observations of physiological changes in the crop during the winter months indicate a reduction or complete absence of the dormant period, leading to plant elongation, depletion of reserve substances, and an increased risk of freezing during sudden cold snaps. The analysis of agronomic risks revealed heightened activity of pathogens such as *Phoma lingam* and *Alternaria brassicae*, as well as pests, necessitating the reinforcement of plant protection systems during this period.

A comparison of yields during traditional and warm winters confirms a decline in crop productivity by 12-18%, attributed to uneven plant development and increased competition among weakened seedlings. However, the application of adaptation measures – such as frost-resistant varieties, growth regulators, and fungicidal treatments – partially mitigates the adverse effects of warm winters. Remote sensing proved effective in the early detection of stress factors and in facilitating the adjustment of agricultural practices. In particular, A. Bhattacharya (2022) and M. Majaura *et al.* (2024) examined the impact of temperature fluctuations on the development of agricultural crops, with a focus on cold stress and microclimate regulation through agroforestry. A. Bhattacharya (2022) highlighted those low temperatures inhibit growth, hinder the formation of generative organs, and disrupt photosynthesis, whereas the present study identified the inverse problem associated with abnormally warm winters: prolonged vegetative growth during December-February, plant elongation up to 27-28 cm, loss of physiological dormancy, and increased susceptibility to pathogens. M. Majaura *et al.* (2024) demonstrated the positive influence of tree strips and shelterbelts on agroecosystems by reducing daily temperature fluctuations and enhancing soil moisture retention. These findings align partially with the importance of microclimatic factors; however, this study emphasised adaptive agronomic strategies – such as the use of rapeseed varieties with enhanced resistance to unstable winter temperatures, growth regulator application, and modified sowing dates – which contributed to improved overwintering of crops under average winter temperatures of +1...+7°C.

Additionally, B.K. Klatt *et al.* (2021) and L.M. Butkevičienė *et al.* (2021) examined the impact of altered winter conditions and sowing dates on oilseed rape productivity, which partially aligns with the findings of this study. B.K. Klatt *et al.* (2021) demonstrated that abnormally warm winters disrupt the synchrony of flower bud development and lead to uneven flowering – observations that are consistent with those reported here. However, the present study extends beyond these conclusions by considering mitigation strategies, particularly the use of frost-resistant varieties and fungicidal treatments. L.M. Butkevičienė *et al.* (2021) emphasised that selecting the optimal sowing date is critical for the yield of spring oilseed rape, whereas this study focussed on technological approaches that stabilise the development of winter oilseed rape irrespective of climatic fluctuations during the winter period.

Furthermore, Z. Tian *et al.* (2021) and X. Li *et al.* (2022) analysed the potential of rapeseed cultivation in the context of food security and optimised crop management under changing climatic conditions. Z. Tian *et al.* (2021) studied the effectiveness of rapeseed as a cover crop on winter pastures in China, highlighting its adaptability to a limited growing season. While this points to the agronomic flexibility of rapeseed, in the Ukrainian context, the central challenge lies not in expanding cultivation areas, but in ensuring stable productivity under abnormally warm winters, where the loss of natural dormancy critically impairs generative organ development and winter hardiness. X. Li *et al.* (2022) concluded that adaptive crop management through optimised agrotechnology can significantly reduce the risk of yield loss – an assertion that aligns with this study's findings regarding the efficacy of growth regulators, fungicide applications, and remote monitoring. However, the present work offered a more detailed analysis of specific adaptation measures for rapeseed under anomalously warm winter conditions.

In particular, L. Hájková *et al.* (2021) and L. Liu *et al.* (2022) explored the influence of climatic factors on rapeseed development, focusing on phenological changes and physiological adaptations. L. Hájková *et al.* (2021) found that meteorological variables – especially average daily temperature and precipitation – significantly affect the timing of rapeseed flowering, a conclusion consistent with the present study's observation of uneven flower bud development and altered flowering timelines during warm winters. L. Liu *et al.* (2022) investigated the mechanisms of winter memory in *Brassica rapa* and demonstrate that temperature fluctuations influence the expression of genes associated with root development and resistance to spring stress. While these findings support the importance of physiological adaptation in maintaining crop productivity, the current study provided a more practice-oriented perspective, focusing on concrete agrotechnical strategies to manage such climatic variability.

In addition, R. Tiwari *et al.* (2021) and T. Murtza *et al.* (2021) analysed the risks associated with changing winter conditions, particularly the impact of weeds and diseases on oilseed rape productivity. R. Tiwari *et al.* (2021) investigated the patterns of winter and summer weed emergence in *Brassica carinata* crops, noting that warm winters contribute to the enrichment of the weed species structure, which competes with cultivated plants for moisture, light, and nutrients. These observations partially correlate with the findings of this study, which established that increased winter temperatures lead to uneven growth of oilseed rape, resulting in heterogeneous stand density. This, in turn, intensifies intra-field competition. Thus, both increased weed pressure and crop morphological heterogeneity complicate development and contribute to yield reduction under abnormally warm winter conditions. T. Murtza *et al.* (2021) found that the development of white spot (*Neopseudocercosporella capsellae*) depends not only on temperature but also on humidity levels, which can significantly increase rapeseed damage during warm winters. The data from this study confirmed the importance of integrated plant protection methods; however, unlike previous research, this work additionally analysed measures to enhance rapeseed resistance through breeding and the use of adaptive treatment technologies.

Moreover, G. Langangmeilu *et al.* (2023) and F. Zeng *et al.* (2025) examined technological aspects of optimising rapeseed cultivation under climate change. G. Langangmeilu *et al.* (2023) demonstrated that sowing dates and temperature regimes affect the morphological characteristics and productivity of rapeseed, which aligns with the findings of this study. However, the present work provided a more in-depth analysis of how warm winters alter crop physiology and identifies methods to mitigate these impacts. F. Zeng *et al.* (2025) employed remote sensing to monitor rapeseed growth at various stages, confirming the effectiveness of crop monitoring technologies discussed in this study. Their findings supported the use of remote sensing as a valuable tool for the timely detection of stress zones in crops and complement this study's approach, which included a comprehensive assessment of remote monitoring in risk prediction and adaptive adjustment of agricultural technologies to stabilise yields.

In particular, L. Li *et al.* (2023) and A. Rezaizad *et al.* (2025) investigated factors influencing the development of winter rapeseed at different stages, emphasising the importance of water regimes and the optimisation of growing periods. L. Li *et al.* (2023) found that excessive soil moisture increases greenhouse gas emissions and reduces rapeseed yield, confirming the critical role of moisture regulation during cultivation. This study also highlighted the need to consider water balance, especially in warm winter conditions, where elevated humidity promotes pathogen development and disrupts plant growth. A. Rezaizad *et al.* (2025) examined the response of promising winter rapeseed lines to delayed sowing, emphasising the influence of agronomic timing on overall crop productivity. The conclusions of this study are consistent with these findings, demonstrating that optimising sowing time and moisture conditions are key to stabilising rapeseed yields.

Also, M.A. Secchi *et al.* (2022) and M.R. Safari *et al.* (2023) analysed strategies for adapting winter rapeseed to climate change, examining the influence of biological factors and regional characteristics. M.R. Safari *et al.* (2023) studied the effects of biofertilizer application and drought stress on the quantitative and qualitative characteristics of different rapeseed varieties, emphasising that the adaptive potential of the crop depends on agrotechnical approaches and resistance to adverse conditions. This study, however, showed that an integrated approach, including the selection of frost-resistant varieties and agronomic adjustments to growing technologies, plays a more important role in stabilising crop productivity. M.A. Secchi *et al.* (2022) analysed the potential for rapeseed oil production in different regions of the USA, emphasising that the success of cultivation depends on local climate and soil conditions. This confirms the findings of this study on the importance of a regional approach in adapting rapeseed cultivation technologies to changing climate conditions.

In addition, D. Rajković *et al.* (2023) and V. Potopová *et al.* (2025) considered the impact of mathematical models and bioclimatic forecasts on rapeseed productivity, which complements the approach used in this study. V. Potopová *et al.* (2025) integrated the DSSAT model with regional climate models to optimise rapeseed and other crop production, demonstrating that accurate prediction of climate change allows for improved adaptive agricultural technologies. The results obtained are partially consistent with the findings of this study, which also emphasised the need for regional adaptation of rapeseed cultivation technologies to minimise climate risks. D. Rajković *et al.* (2023) used neural networks and the random forest method to predict the content of fatty acids and tocopherols in rapeseed oil, proving that such models can be effective in assessing product quality. The data from this study confirm the promising application of digital technologies in agriculture, which correlates with the results of this study, emphasising the importance of remote monitoring and forecasting of climate risks. Thus, the results of this study confirm and extend the conclusions of previous works, suggesting a more comprehensive approach to the adaptation of winter rapeseed.

CONCLUSIONS

The study analysed the impact of abnormally warm winters on the growth, development, and yield of winter rapeseed. It was found that an increase in the average winter temperature by 3.2-4.8°C compared to long-term indicators caused significant physiological changes in the plants. A reduction or complete absence of the dormancy period was observed in 87% of the studied crops, which led to premature elongation of plants by 15-22% and depletion of reserve substances by 28-35%. These changes reduced the overall winter hardiness of the crop and increased the risk of damage during sudden cold snaps. Agronomic risks caused by a warm winter were also identified, including increased pathogen activity. The frequency of *Phoma lingam* infection rose to 54%, and *Alternaria brassicae* to 39%, significantly exceeding rates recorded under traditional winter conditions. Additionally, elevated pest activity was observed, increasing stress factors for the crop. Yield analysis indicated a decline of 12-18%, and in some cases up to 25%, which poses a critical threat to stable agricultural production.

The effectiveness of adaptation measures in mitigating the negative impact of climate change was assessed. The use of frost-resistant varieties improved overwintering and reduced the risk of freezing during abrupt temperature drops. The application of growth regulators prevented excessive plant elongation, while fungicidal treatments reduced disease incidence by 16-21%. As a result, these adaptation measures led to a reduction in crop losses by 8-14%. The findings underscore the need to adapt rapeseed cultivation technologies to a changing climate, particularly in response to rising average winter temperatures, shortened dormancy periods, and increasing biotic stress. It was established that traditional agrotechnical approaches require revision, considering changes in crop phenological dynamics under abnormally warm winter conditions. The proposed strategies – including optimisation of sowing dates, application of growth regulators, use of frost-resistant varieties, and reinforcement of phytosanitary control – enable the minimisation of adverse weather impacts. Practical implementation of these measures helps reduce the risks of plant elongation, depletion of carbohydrate reserves, and loss of uniform stand density, while also limiting the development of pathogens and pests whose activity intensifies during mild winters. Future research should focus on expanding the dataset, analysing long-term changes in rapeseed productivity, and refining adaptation strategies in line with projected climate trends.

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Особливості вирощування ріпаку озимого за аномально теплих зим

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Анотація. Актуальність дослідження зумовлена впливом змін клімату на вирощування ріпаку озимого в Україні. Метою дослідження було оцінити вплив нестабільних зимових умов на розвиток і врожайність ріпаку озимого та визначити ефективні заходи для мінімізації пов'язаних ризиків. У роботі досліджено вплив аномально теплих зим на ріст, розвиток та продуктивність ріпаку озимого. Проведено комплексний аналіз агрономічних ризиків, що виникають за умов нестабільного зимового клімату, зокрема скорочення або повної відсутності періоду спокою, витягування рослин, виснаження запасних речовин і посилення активності патогенів (*Phoma lingam*, *Alternaria brassicae*). Досліджено особливості фізіологічних змін у ріпаку, пов'язані з підвищенням середньої зимової температури на 3,2-4,8 °C, що спричинило втрату зимостійкості у 87 % рослин, збільшення рівня ураженості хворобами на 39-54 % та зниження врожайності на 12-18 %, у деяких випадках – до 25 %. Проведено оцінку ефективності адаптаційних заходів, серед яких використання морозостійких сортів, регуляторів росту та фунгіцидних обробок. Встановлено, що їхнє застосування дозволило зменшити втрати врожаю на 8-14 % і покращити загальну стійкість ріпаку до кліматичних стресів. Крім того, використання дистанційного зондування підвищило ефективність моніторингу посівів, забезпечивши точність виявлення стресових ділянок на 23 % вище в порівнянні зі стандартними методами спостереження. Отримані висновки підкреслюють важливість адаптації технологій вирощування ріпаку до змінного клімату. Запропоновані стратегії дозволяють мінімізувати негативний вплив теплих зим, стабілізувати врожайність та забезпечити ефективне управління агросистемами. Дані результати можуть бути корисними для аграрного сектору, сприяючи підвищенню ефективності вирощування ріпаку озимого та розробці нових адаптаційних технологій для сільськогосподарського виробництва

Ключові слова: температурні аномалії; стресові чинники; мікроклімат посівів; технологічна реакція культур; агрокліматичні умови