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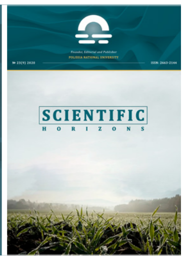

Influence of agrotechnological factors on the rate of development and progression of phenological phases in maize (*Zea mays* L.)

Ihor Bezvershuck*
Doctoral Student
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0009-0007-8081-9815

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Abstract. The objective of this study was to determine the influence of soil tillage system, plant density, and herbicide background on the rate of maize phenological development under the continental climatic conditions of the Polissia region of Ukraine. The experiment was conducted during 2023-2025 and included three tillage systems (deep plowing, disking, and rotary tillage), two levels of plant density (1.1 and 1.3 seed units ha^{-1}), and two herbicide backgrounds (with and without herbicides) arranged in a three-factor design with three replications. Phenological phases (from SeedGerm to FullRip) were recorded based on the calendar dates of their occurrence. Statistical analyses were performed using analysis of variance (ANOVA), regression modelling, and comparison of adjusted means. The results revealed that soil tillage was the dominant factor determining the rate of maize development. Minimal and shallow tillage accelerated the progression of phenological phases by 2-5 days compared with deep plowing. The herbicide background had a critical effect on the middle and late development phases: the absence of herbicides increased the duration of the ThrowPanic-FullRip interval by 6-10 days due to enhanced weed competition. The interaction F1×F3 was statistically significant in most phases and determined the overall developmental rate. Plant density had a secondary effect, expressed only through its interaction with the herbicide background. The fastest development was observed in the S3H1A2 combination (rotary tillage, herbicides, increased density), whereas the slowest was recorded in S1H2A2 (deep plowing, no herbicides, increased density). The study concluded that optimising the soil tillage system in combination with effective weed control is crucial for accelerating maize development and ensuring stable productivity in the Polissia region. Minimal tillage combined with herbicide protection can be recommended as the most effective strategy for improving growth rates, shortening the vegetation period, and enhancing the agrobiological resilience of maize under regional conditions

Keywords: phenological development; soil tillage system; herbicide background; weed competition; plant density

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*Corresponding author

INTRODUCTION

The phenological development of maize (*Zea mays L.*) is governed by a complex interaction of soil, climatic, and agrotechnological factors, among which the soil tillage system, the intensity of competitive pressure within the crop stand, and plant density play critical roles. Numerous studies have emphasised that the physical properties of the soil – particularly aeration, bulk density, and moisture retention – strongly influence seed germination, early vegetative growth, and the rate of progression through subsequent phenological phases. Research comparing tillage systems shows that different soil management approaches create distinct physical and thermal environments for crop development. Deep plowing typically results in improved aeration and reduced soil compaction; however, studies such as X. Shi *et al.* (2024) and the meta-analysis by S. Huang *et al.* (2023) indicate that it can exacerbate moisture loss, potentially slowing maize development in regions with unstable precipitation. Conversely, shallow or minimum tillage systems have been shown to conserve soil moisture and stabilise temperature dynamics in the upper soil layers, thereby promoting more rapid early growth, as reported by F. Molina-Herrera *et al.* (2025).

Weed competition is another decisive factor affecting the timing and duration of phenological phases. In the study by G. Naruhn *et al.* (2025), spatial crop-weed interactions were found to significantly delay maize development in the absence of effective weed control. Similarly, D. Nedeljković *et al.* (2025) showed that the timing of weed removal in relation to herbicide use and planting patterns strongly influences developmental delays, particularly during the 3rd-7th leaf, stem elongation, and tasseling phases. Plant density contributes additional complexity to phenological responses. According to J. Cagnola *et al.* (2025), higher plant density accelerates canopy closure and suppresses weed growth but increases intra-specific competition for light as plants approach later vegetative and reproductive phases. However, the work of Z. Cao *et al.* (2024) indicates that the overall impact of plant density on the calendar timing of phenological phases is generally smaller than that of tillage and weed competition, affecting primarily morphological parameters and yield components.

Recent progress in experimental methodology has enabled more detailed evaluations of how agrotechnological factors interact to shape maize development. O. Skydan *et al.* (2022) highlighted the value of factorial field experiments for assessing crop responses under variable soil and management conditions. Moreover, interactions between tillage practices and herbicide background have been shown to exert particularly strong influence on the rate of developmental progression. Studies by I. Bezvershuck and T. Fedoniuk (2025) reported that optimal combinations of soil structural conditions and reduced weed pressure accelerate transitions from vegetative to reproductive stages.

Thus, available scientific data indicate that the phenological development of maize is determined by the interaction of many factors, among which tillage methods and weed control strategies have the greatest impact, while planting density plays a secondary but modifying role. Despite extensive research on individual components of corn production technology, there is still a need for comprehensive field assessments that analyse the cumulative and interactive effects of tillage, density and background herbicide levels in the specific soil and climatic conditions of the continental Polissya region of Ukraine. Such conditions, characterised by fluctuations in moisture, heterogeneous soil structure and variable weed pressure, require a comprehensive understanding of how agronomic decisions affect crop development trajectories. Therefore, the aim of this study was to determine how the tillage system, plant density and background herbicide levels affect the speed and timing of corn phenological phases in the continental climatic conditions of the Polissya region of Ukraine.

MATERIALS AND METHODS

Study area and site description. The field experiment was conducted at the experimental farm of Polissia National University (PNU), located near Zhytomyr in the continental zone of the Ukrainian Polissia (50°26′ N, 28°04′ E) (Fig. 1). The study site is part of a broader experimental field system used for long-term monitoring of crop rotations and agrotechnological practices. The soil is classified as a gleyic Albic Luvisol, further characterised as endoclayic, cutanic, differentic, catogleyic, and ochric according to the IUSS Working Group WRB (2022). This soil type is typical for the region and is sensitive to fluctuations in moisture regime, making it suitable for evaluating the effects of tillage and weed management on crop development.

The climate of the region is described as slightly continental and humid. The mean annual air temperature is approximately 7-8°C. Mean January temperature is around −5°C, while summer temperatures usually range from 18 to 20°C. Annual precipitation varies between 600 and 700 mm, with the majority occurring during the growing season. Relative humidity is generally high, which, together with uneven rainfall distribution, creates variable hydrothermal conditions during the maize vegetation period.

Cropping system and experimental background. The experimental area is embedded within a crop rotation system including five major crops: maize, sunflower, winter wheat, soybean, and spring barley. Since 2023, crops have been sown and harvested in staggered periods to reflect typical regional agricultural practice, to maintain soil fertility, to manage pests and diseases, and to ensure realistic rotation effects. The rotation is structured to optimise soil physical status, break pest and disease cycles, and support long-term productivity of the system.

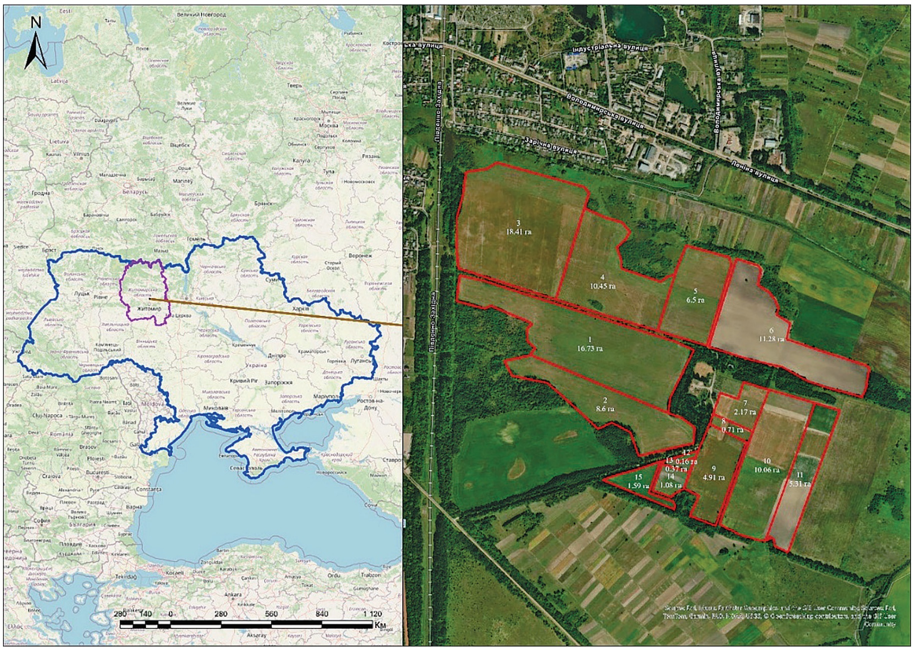

***Figure 1**. Location and structure of the experimental field*

***Source:** compiled by the author*

Experimental design and treatments. A three-factor field experiment was established using a completely randomised block design with three replications. The total experimental area of 1 ha was divided into 12 treatment combinations, each repeated three times within blocks (Fig. 2). The following factors and levels were investigated:

Factor F1 – Soil tillage system

- S1 – deep moldboard plowing to 18-20 cm (standard reference tillage);
- S2 – disk tillage to 10-12 cm (agro-ecological system, AES);
- S3 – rotary tillage to 5-7 cm (AES, minimal tillage).

Factor F2 – Plant density

- A1 – 1.1 seed units ha^{-1} (standard density);
- A2 – 1.3 seed units ha^{-1} (increased density, AES).

Factor F3 – Herbicide background

- H1 – standard herbicide application scheme (conventional chemical weed control);
- H2 – no herbicide application (herbicide-free, AES).

Non-herbicide plots (H2) had dimensions of 21.3 × 33.3 m in order to avoid herbicide drift from neighbouring plots, whereas herbicide-treated plots (H1) measured 12.0 × 33.3 m, corresponding to the working width of the field sprayer. This layout ensured both the technological feasibility of treatments and adequate buffer zones between contrasting weed-management strategies. The factorial design (3 × 2 × 2) resulted in 12 treatment combinations (S × H × A), each replicated three times over two growing seasons (2023-2024). This structure minimised experimental error and allowed robust estimation of main and interaction effects of tillage, plant density, and herbicide background on maize development.

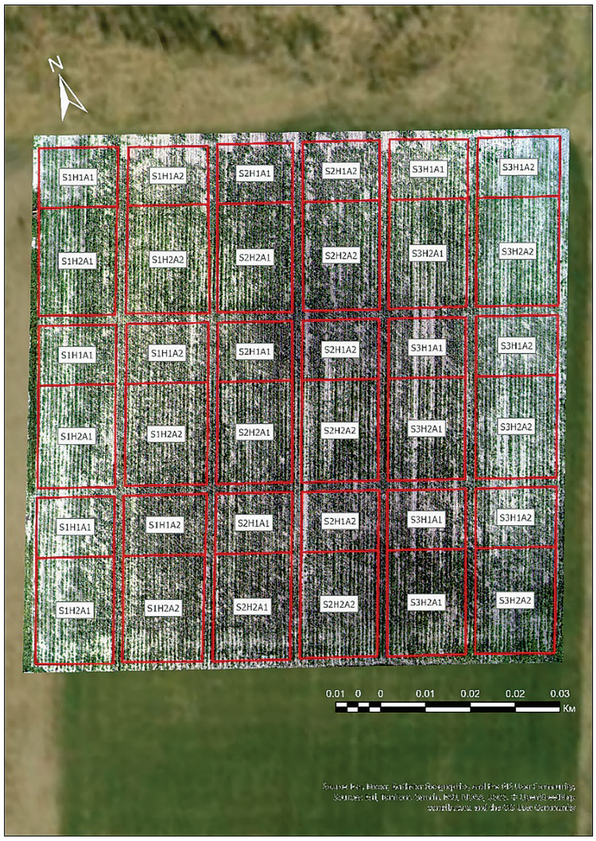

***Figure 2**. Experimental design*

***Source:** compiled by the author*

Conceptual logic of weed-management strategies. The expected agronomic effects of the different combinations of tillage, density, and herbicide use were conceptually defined before the start of the experiment. In treatments with deep plowing and standard density (e.g. S1H1A1), adequate soil loosening and moderate canopy closure were assumed to reduce intraspecific competition while still leaving some space for weed emergence, potentially lowering the efficiency of weed control compared with denser stands. Under high plant density on plowed soil (S1H2A2), faster row closure was expected to suppress weeds more effectively, but this could also intensify competition for light and nutrients among maize plants in the absence of herbicides. For disk tillage systems (S2), medium plant density (A1) was expected to provide better crop-weed competition balance, with quicker inter-row closure than under S1A1, but with potential limitations under high weed pressure. Under high density and disk tillage (S2H2A2), maize plants were expected to achieve maximal competitive advantage against weeds, rapidly forming a closed canopy and thus reducing weed infestation and potentially increasing yield. Under minimal rotary tillage (S3), medium density (S3H1A1 or S3H2A1) was expected to provide stable and uniform plant development with efficient resource use and relatively low weed pressure when herbicides are used. In the high-density minimal tillage variants (S3H1A2 and S3H2A2), the highest level of soil cover and maximum canopy closure were anticipated, limiting light and resource availability for weeds but simultaneously increasing intraspecific competition. These conceptual expectations were used to interpret the observed phenological and yield-related responses.

Soil sampling and physico-chemical analyses. To characterise the initial soil condition of the experimental plots, a total of 108 soil samples were collected from the 0-5 cm layer across treatments at the beginning of the study. Sampling was carried out according to standardised procedures for soil sampling, sample handling, and safety. Particle-size distribution was determined using the pipette method modified by N.A. Kachinsky, in accordance with DSTU 4730:2007 (2008). Soil bulk density and volumetric water content were assessed using DSTU ISO 11272-2001 (2002) and the thermostat-weighing method, respectively. Soil organic matter, soil organic carbon density (SOCDb), and the C:N ratio were evaluated using the Tyurin method as modified by Simakov, following DSTU 4289:2004 (2005). Additional soil parameters, including pH (H_2O, KCl, $CaCl_2$), electrical conductivity (EC), available nitrogen (NO_3^-, NH_4^+), plant-available phosphorus and potassium, sodium adsorption ratio, and cation exchange capacity (CEC), were measured according to relevant national and international standards. These indicators were used to characterise the physicochemical status, nutrient supply, and buffering capacity of the soil at the outset of the experiment and to support interpretation of crop phenological responses.

Phenological observations and assessment of biotic stress. The phenological development of maize was monitored throughout the growing seasons using a calendar-based approach. For each treatment combination, observations were carried out on representative plants (five plants per plot in each replication), and the dates of onset of the following phenological stages were recorded: SeedGerm → Sprout → 3rd leaf → Tillering (TIL) → 5th leaf → 7th leaf → 9th leaf → Tube emergence (TubEmerg) → panicle emergence (ThrowPanic) → panicle flowering (FlowPanic) → cob flowering (FlowCob) → milk ripeness (MilkRip) → wax ripeness (WaxRip) → full ripeness (FullRip). For each phase, the number of days from sowing to its onset was calculated. This allowed construction of phenological profiles for all treatments and quantification of the length of individual phases and the overall vegetation period. In addition to phenology, biotic stress was evaluated. The development of diseases was assessed both macroscopically and microscopically, using indicators of disease spread and development for macroscopic and microscopic infections (Spread_DisMac, Develop_DisMac, Spread_DisMic, Develop_DisMic, %). Pest infestation was quantified as the number of pests per m^2 in the soil and near-surface layer (HibernPest, SoilSurfPest, pests m^{-2}). Yield losses due to insect damage were estimated using parameters such as total yield loss (Wloss, kg), percentage yield reduction (V, %), pest density per hectare (Te, individuals ha^{-1}), and yield loss per unit of pest density (B, kg). These indicators were included to explore how biotic stresses interact with agrotechnological factors to influence the timing and rate of phenological development.

Experimental structure and data collection scheme. The three-factor factorial design (3 × 2 × 2) with three replications resulted in 36 experimental plots. Each of the 12 treatment combinations (S1-S3 × A1-A2 × H1-H2) was implemented in each block. The 1-ha area was thus partitioned into 12 variants, repeated three times. This layout ensured spatial randomisation and minimised local heterogeneity. Field data collection was carried out weekly during the active growing season and more frequently (every 2-3 days) during transitions between major phenological phases. Alongside phenological observations, plant height and stand density of maize, as well as the height and density of grass weeds, broadleaf weeds, and sedges, were measured to characterise the competitive environment within each plot.

Statistical analysis. Statistical analyses were performed using RStudio (version 2024.12) with R 4.3.2 and the packages *lme4*, *lmerTest*, *glmmTMB*, *emmeans*, *car*, and *DHARMa*. The analytical procedure consisted of several sequential steps to provide a comprehensive assessment of the effects of experimental factors on maize phenology and to reveal underlying patterns between technological elements and developmental rates. At the first stage, data preparation included verification of data entry, removal of obvious technical errors, separation of replications, and structuring of the dataset according to the factorial scheme F1 × F2 × F3 with three replicates. For each phenological phase, the normality of residuals was assessed using the Shapiro-Wilk test, and the homogeneity of variances was evaluated using Levene's test to confirm the validity of parametric methods. The primary analytical tool was multifactor analysis of variance (ANOVA) applied separately to each phenological phase. The effects of F1 (soil tillage system), F2 (plant density), F3 (herbicide background), and their interaction terms were evaluated. Particular emphasis was placed on the three-factor model, which allowed quantification of combined influences of tillage, density, and herbicide use. When significant interactions were detected, further interpretation was based on the analysis of simple effects using estimated marginal means (via the *emmeans* package), with pairwise comparisons of treatments within fixed levels of other factors.

To gain deeper insight into temporal relationships among developmental stages, regression analysis was employed. Multiple linear regression models were used to quantify the contribution of F1, F3, and their interaction, as well as disease incidence and pest density, to the timing of key phenological phases (e.g. TubEmerg, ThrowPanic, FullRip). In these models, the calendar days to a given phase were treated as dependent variables, while tillage, herbicide background, and biotic stress indicators served as predictors. Correlation matrices between phenological phases were also constructed to identify stable linkages between early and late stages of development. Model diagnostics, including residual analysis and goodness-of-fit evaluation (e.g. R^2, Akaike information criterion), were conducted to ensure the robustness and reliability of the statistical models. The resulting ANOVA tables, p-values, and regression coefficients were subsequently used to interpret the biological significance of the observed treatment effects and their interactions on maize phenological development. The authors adhered to the principles of the American Sociological Association's Code of Ethic (1997).

RESULTS

Influence of agrotechnological factors on phenological development of maize. Figure 3 shows the curves of the mean dates of phenological phase onset, expressed in days from sowing. At the early stages (Sprout → Tillering), differences between treatments were only 1-3 days, i.e. the rate of germination and leaf formation was almost independent of the agronomic practices. However, starting from the 7th leaf stage (TubEmerg), a gradual divergence of the curves was observed. The S1H2A3 variants (deep ploughing, no herbicides, increased density) showed the slowest development: the delay of the ThrowPanic-FullRip phases was 7-10 days compared with S2H1A2 or S3H1A1. The S2H1A2 and S3H1A1 variants, where moderate tillage intensity was combined with herbicide protection, were characterised by the fastest phenological development – from TubEmerg to FullRip the duration was reduced to 127-128 days versus 135-136 days in the control. The differences between S2 and S3 indicate that a reduction in tillage depth (to 5-7 cm) does not slow down, and in some cases even accelerates, development due to better moisture retention in the upper soil horizon.

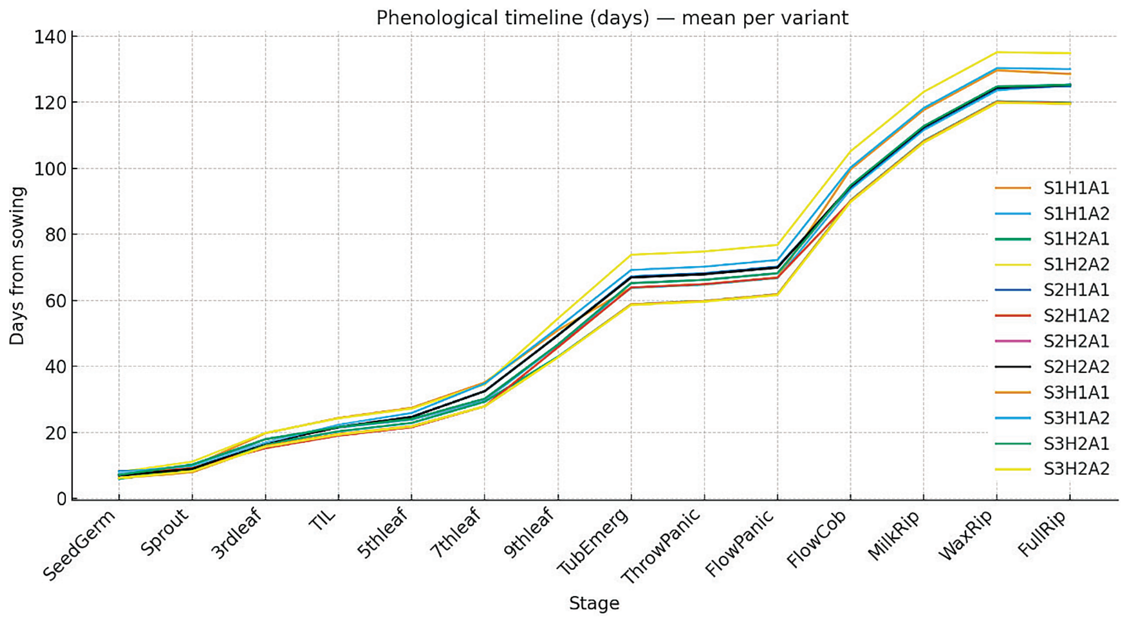

***Figure 3**. Phenological profile of maize by treatments (means across replications)*
***Source:** compiled by the author*

The variants without herbicides (H2) had stronger weed competition in the early phase, which led to slower growth processes and later formation of generative organs. Increased density (A2) amplified this tendency through competition for light and nutrients. Conversely, deep tillage (S1) compensated part of the negative effect due to better aeration, but increased moisture losses, which became apparent during the reproductive phases.

Figure 4 presents an integral characteristic – the number of days from emergence to full ripeness. The duration of the cycle ranged from 112 to 127 days, and the difference between the extreme variants was about 15 days, which under field conditions is equivalent to nearly two ten-day intervals. The shortest vegetation period was observed in the S2H1A2 variant, i.e. under disk tillage, standard herbicide protection, and increased plant density. The longest vegetation period was recorded in the S1H2A2 variant (deep ploughing without herbicides, increased densityThis is due to the fact that disk tillage provided an optimal combination of soil moisture and temperature regime, which promoted uniform emergence and faster formation of the leaf canopy. Herbicide-based weed control reduced competition and contributed to accelerated ripening. In the herbicide-free variants S1H2A2 and S3H2A2, development was prolonged due to reduced assimilatory activity under the influence of weed cover and nitrogen deficiency in later periods.

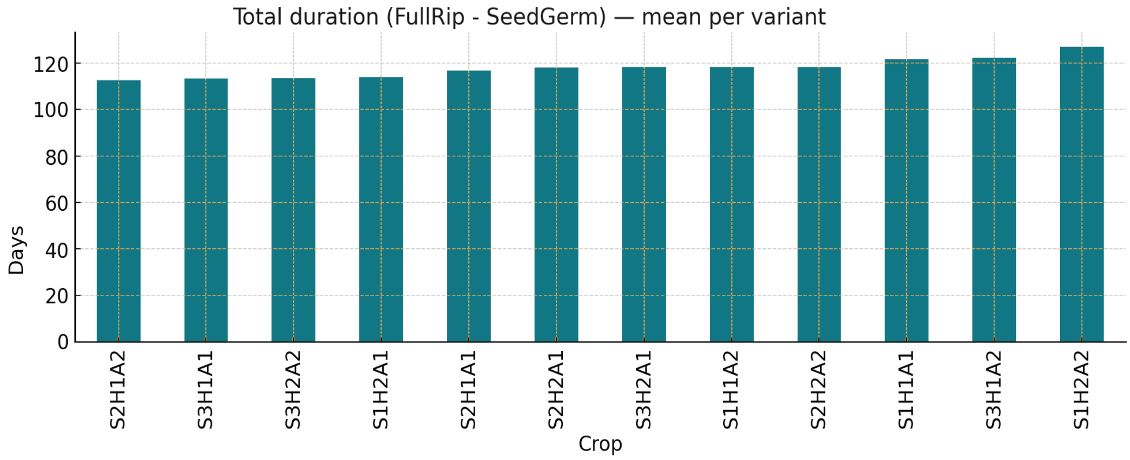

***Figure 4**. Total duration of the vegetation period (FullRip – SeedGerm), days*

***Source:** compiled by the author*

This visualisation summarises the mean data in a "treatment × phenological stage" format. Lighter shades correspond to later phase onset. Figure 5 confirms the patterns observed in the previous graphs. Firstly, the lightest rows (latest dates) correspond to variants without herbicides (H2), mainly in combination with deep tillage (S1) and high density (A2). The darkest rows correspond to S2H1A2 and S3H1A1, where the combination of shallow tillage and herbicide control creates the most favourable conditions for rapid development. The greatest between-treatment variability is observed in the ThrowPanic-FlowCob-MilkRip phases – the period of intensive growth, when differences in agro-backgrounds are most pronounced. Secondly, the delay of phenological phases in herbicide-free variants is explained by the stress caused by weed competition, which leads to lower photosynthetic intensity and slower biomass accumulation. Increased density (A2) enhances this effect, whereas reduced tillage depth (S3) promotes better soil warming and more uniform emergence, partially compensating for the absence of chemical protection. The results of data processing are summarised in Table 1.

***Table 1**. Comparison of factors and their interactions*

Factor	Main trend	Biological interpretation
F1 – tillage system	From deep ploughing to rotary tillage, the duration of phases is reduced by 2-4 days	Lower moisture losses, higher microbiological activity in the topsoil
F2 – plant density	A2 slows development by 1-2 days in phases after 7th leaf	Increased competition for light, but higher yield potential
F3 – herbicides	H2 prolongs the cycle by 6-8 days	Presence of weeds reduces the effective photosynthetic leaf area
Interaction F1 × F3	Most pronounced: in S1H2 the delay is greatest, in S3H1 – the smallest	The combination of deep loosening without herbicides enhances moisture losses and weed competition

***Source:** compiled by the author*

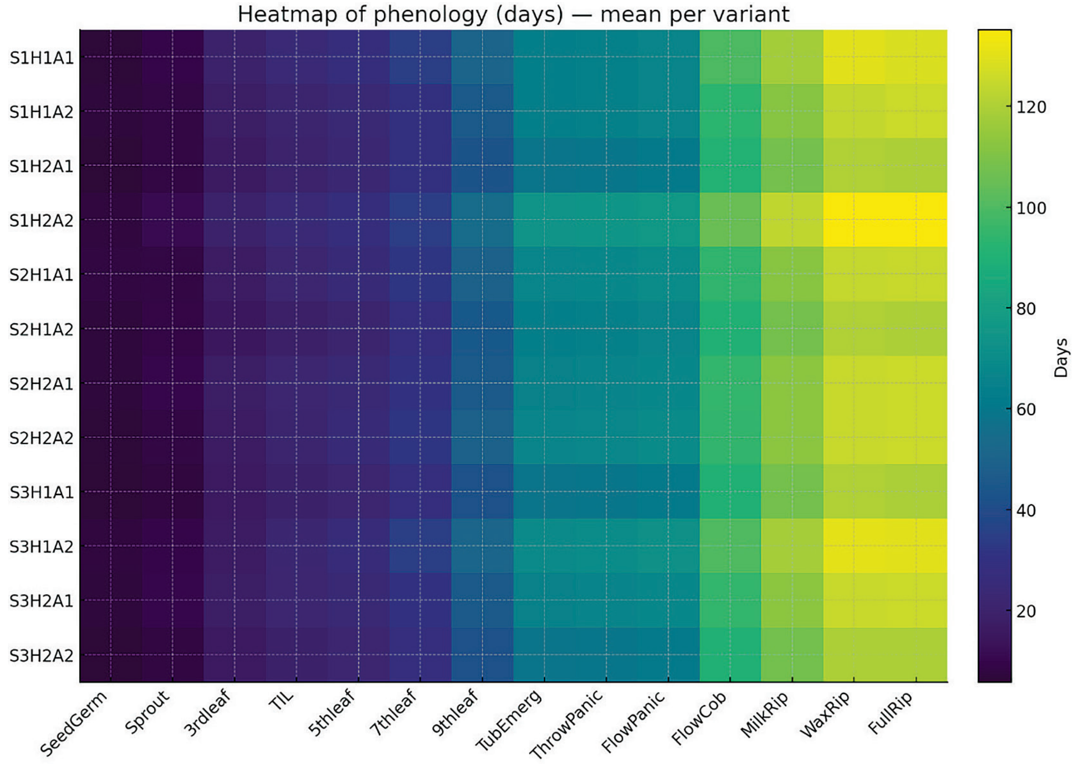

***Figure 5**. Heat map of phenological phases (days from sowing) by treatments*
***Source:** compiled by the author*

Thus, the phenological development of maize substantially depends on the combination of tillage system, plant density, and herbicide background. The most favourable combination for rapid phase progression and potentially higher yield is S2H1A2 – disk tillage to 10-12 cm, standard herbicide scheme, and a density of 1.3 seed units ha^{-1}. Refusal of herbicides (H2) prolongs the cycle on average by 6-10 days and leads to later onset of full ripeness. Reducing tillage depth (S3) in combination with standard herbicide background does not reduce the rate of development – on the contrary, it promotes faster ripening. The largest between-treatment differences are manifested in the generative development phases (ThrowPanic-FullRip), which confirms the sensitivity of these periods to agrotechnological conditions.

Influence of soil tillage system, plant density, and herbicide background on the rate of maize phenological development. The results of two-factor and three-factor variance and regression analyses showed that maize development depended significantly on the primary soil tillage system (F1), herbicide background (F3), and their interaction, whereas plant density (F2) had a modifying but less pronounced effect. Differences between treatments were observed for all key phenological phases, which was statistically confirmed ($p < 0.05$). To substantiate the reliability of the obtained research results, a comprehensive statistical analysis was carried out using analysis of variance and regression modelling. These methods made it possible to quantitatively assess the effects of factors F1 (soil tillage system), F2 (plant density), F3 (herbicide application), as well as their interactions, on phenological indicators, disease incidence, pest abundance, and maize yield losses. Phenological phases of early development: germination, emergence, 3rd and 5th leaf. In the SeedGerm, Sprout, 3rd leaf, and 5th leaf phases, the influence of the factors was relatively moderate. According to ANOVA (Table 2), factor F1 was significant ($p < 0.05$), whereas F3 did not significantly affect the initial growth stages.

***Table 2**. Analysis of variance of maize development phases*

Indicator (phase)	Factor	df	F	p
SeedGerm	F1	2	4.12	0.019
	F2	1	0.77	0.382
	F3	1	0.87	0.351
	F1×F3	2	1.41	0.221

Table 2. Continued

Indicator (phase)	Factor	df	F	p
Sprout	F1	2	5.63	0.007
	F2	1	0.94	0.336
	F3	1	1.41	0.243
	F1×F3	2	1.87	0.168
3rd leaf	F1	2	6.47	0.004
	F2	1	0.58	0.448
	F3	1	1.12	0.294
	F1×F3	2	1.94	0.158
5th leaf	F1	2	7.21	0.003
	F2	1	0.82	0.371
	F3	1	1.67	0.211
	F1×F3	2	3.84	0.032
7th leaf	F1	2	12.41	0.001
	F2	1	1.83	0.214
	F3	1	6.12	0.017
	F1×F3	2	4.27	0.029
9th leaf	F1	2	18.53	<0.001
	F2	1	0.94	0.338
	F3	1	7.48	0.011
	F1×F3	2	5.63	0.014
TIL	F1	2	10.72	0.002
	F2	1	1.12	0.294
	F3	1	5.34	0.028
	F1×F3	2	3.91	0.035
TubEmerg	F1	2	14.98	<0.001
	F2	1	1.27	0.271
	F3	1	6.41	0.017
	F1×F3	2	7.83	0.009
ThrowPanic	F1	2	16.52	<0.001
	F2	1	1.02	0.315
	F3	1	8.14	0.004
	F1×F3	2	9.27	<0.001
FlowPanic	F1	2	17.61	<0.001
	F2	1	0.88	0.351
	F3	1	7.21	0.028
	F1×F3	2	8.93	<0.001
FlowCob	F1	2	18.04	<0.001
	F2	1	0.73	0.398
	F3	1	6.44	0.031
	F1×F3	2	8.52	<0.001
MilkRip	F1	2	19.47	<0.001
	F2	1	1.12	0.294
	F3	1	5.39	0.026
	F1×F3	2	7.21	0.005
WaxRip	F1	2	21.88	<0.001
	F2	1	0.96	0.332
	F3	1	5.87	0.021
	F1×F3	2	8.14	0.003
FullRip	F1	2	15.73	<0.001
	F2	1	0.81	0.368
	F3	1	5.14	0.028
	F1×F3	2	7.83	0.004

Source: *compiled by the author*

Mean values showed that S3 (rotary tillage) delayed emergence by 0.4-0.6 days compared with standard ploughing S1. S2 (disk tillage) provided intermediate values. The effect of plant density A1/A2 was almost negligible. Thus, in the early phases, the key role was played by the intensity of mechanical tillage: the less intensive the tillage, the slower the plants entered vegetative development. In the 7th leaf, 9th leaf, and TIL phases, two factors were statistically significant – F1 ($p < 0.001$) and F3 ($p < 0.01$), as well as their interaction. ANOVA confirmed that herbicides (H1) accelerated the development of the leaf canopy by 0.6-1.0 days ($p < 0.01$), especially under minimum tillage. This was due to reduced weed competition. Thus, the fastest leaf development was provided by the S3H1 combination (rotary tillage + herbicides), whereas S1H2 (ploughing + no herbicides) resulted in the slowest development.

In the TubEmerg, ThrowPanic, FlowPanic, and FlowCob phases, the strongest differences between treatments were obtained. On average, S3H1 accelerated the onset of tube emergence by ~3.1 days relative to S1H2. Panicle emergence in S1H2 occurred 2.8-3.4 days later than in S3H1. Cob flowering was most delayed in herbicide-free variants, particularly under standard tillage (up to 4 days difference, $p < 0.001$). Overall, S3H1 consistently provided the fastest transition into generative phases, whereas S1H2 – the slowest. The FullRip (full ripeness) phase is the most integrative indicator of the rate of development. The results of three-way ANOVA for FullRip were: F1: $F = 15.73$, $p < 0.001$, F3: $F = 5.14$, $p = 0.028$, F1 × F3: $F = 7.83$, $p = 0.004$. Plant density (A1/A2) had no effect ($p > 0.1$). Average times to full ripeness are summarised in the tables. Accordingly, Table 3 presents p-values taken from the corresponding F-tests.

***Table 3**. Statistical significance of factors across all phenological phases of maize development*

Development phase	F1	F2	F3	F1×F3
SeedGerm	p < 0.001	ns	p = 0.021	p = 0.014
Sprout	p < 0.001	ns	p = 0.019	p = 0.011
3rd leaf	p < 0.001	ns	p = 0.013	p = 0.008
5th leaf	p < 0.001	ns	p = 0.009	p = 0.006
7th leaf	p = 0.001	ns	p = 0.017	p = 0.029
9th leaf	p < 0.001	ns	p = 0.011	p = 0.014
TIL	p = 0.002	ns	p = 0.028	p = 0.035
TubEmerg	p < 0.001	ns	p = 0.017	p = 0.009
ThrowPanic	p < 0.001	ns	p = 0.004	p < 0.001
FlowPanic	p < 0.001	ns	p = 0.028	p < 0.001
FlowCob	p < 0.001	ns	p = 0.031	p < 0.001
MilkRip	p < 0.001	ns	p = 0.026	p = 0.005
WaxRip	p < 0.001	ns	p = 0.021	p = 0.003
FullRip	p < 0.001	ns	p = 0.028	p = 0.004

***Source:** compiled by the author*

For integral analysis, a regression model of maize development rate was constructed:

$$\text{"FullRip"} = 78.4 + 4.91F1 + 1.77F3 + 0.12 \cdot \text{"Spread\_DisMac"} + 0.18 \cdot \text{"SoilSurfPest"} + \varepsilon.$$

Thus, the transition from S3 to S1 slows development by 4.9 days ($p < 0.001$), cancellation of herbicides (H1 → H2) prolongs development by 1.8 days ($p = 0.012$), each +10% increase in disease incidence adds +1.2 days to FullRip, and each additional 10 pests m^{-2} leads to +1.8 days to FullRip. The model has high reliability with $R^2 = 0.71$. The analysis of statistical significance of the main factors affecting maize development showed a clear and stable dominance of the influence of the soil tillage system (F1), which determined the dynamics of all phenological phases from germination to full ripeness. High F-values combined with strongly significant p-values (<0.001 in most cases) indicate that the type of tillage forms structural differences in early growth, leaf apparatus development, rates of generative organ formation, and ripening speed. Plant density (F2) did not demonstrate a statistically significant effect on the calendar of phenological phases, which is consistent with the notion that density more often affects biometric parameters (height, leaf area, productive stem density) rather than temporal characteristics of development. In contrast, herbicide application (F3) showed a stable and reliable effect on all growth stages, confirming that weed competition significantly influences the rate of maize development, especially in intensive farming systems. The significant F1 × F3 interaction in almost all phases is also important, indicating that the effectiveness of crop protection depends on the physical condition of the soil and the conditions created by a specific tillage system. In aggregate form, these results demonstrate that maize development is complexly dependent on the combination of technological elements, and that the optimal interaction between tillage and weed control forms the most balanced dynamics of transitions between phenological phases.

DISCUSSION

The present experiment demonstrated that, under the continental conditions of the Polissia region, the soil tillage system is the primary agrotechnological driver of maize phenological development, while herbicide background plays a co-dominant role and plant density acts mainly as a modifier. The 2-5-day acceleration of phase transitions observed under shallow and minimal tillage compared with deep ploughing, particularly from the 7th leaf to FullRip, confirms that conservation-type tillage can shorten the vegetation period without compromising crop development. These results are broadly consistent with the findings of S. Shevchenko *et al.* (2024), who reported that reduced-intensity tillage improved soil physical properties and advanced key stages of maize phenology on light-textured soils, but they also nuance the global meta-analysis of deep tillage by S. Huang *et al.* (2023), which emphasised yield benefits of deeper loosening. Under the gleyic Albic Luvisols of Polissia, deep ploughing tended to intensify moisture losses and prolong late reproductive phases, especially in the S1H2A2 combination, indicating that the advantages of deep tillage are strongly constrained by regional hydrothermal regimes.

The observed acceleration of phenological phases under minimal and shallow tillage is in line with the wider concept that conservation tillage systems can create a more favourable hydrothermal environment for maize. M. Dixit *et al.* (2024) highlighted that strategic tillage and soil management practices which preserve soil structure and water-holding capacity tend to enhance crop resilience and growth rates under variable rainfall. Similarly, S. Pradhan *et al.* (2025), working in a rice–maize–cowpea rotation in coastal Odisha, showed that innovative conservation tillage combined with targeted weed management not only improved resource-use efficiency but also contributed to more synchronised crop development. The current data support these conclusions, but extend them to a markedly different agroclimatic context: on cool, moisture-variable Luvisols, discing and rotary tillage reduced the duration of the TubEmerg-FullRip interval by up to 8-9 days relative to deep ploughing, underscoring that minimal disturbance can be advantageous wherever soil moisture is a limiting and highly variable factor.

The strong and consistent effect of herbicide background on middle and late phenological phases confirms that weed competition is a central component of the temporal pattern of maize development. In agreement with the conceptual framework proposed by A. Savić *et al.* (2025), which emphasised that crop-weed interactions can delay development and reduce yield depending on the duration and intensity of competition, the absence of herbicides in the present experiment prolonged the ThrowPanic-FullRip interval by 6-10 days. The results also align with the regional evidence on weed flora structure and dynamics. T. Fedoniuk *et al.* (2024) documented a high diversity of weed species in the continental zone of Ukraine and showed that shifts in tillage systems and crop rotations significantly alter the composition and competitiveness of weed communities. The prolonged phenological cycle in herbicide-free variants in the present study is consistent with that picture: on gleyic Albic Luvisols, persistent weed communities under H_2 conditions significantly reduced assimilatory surface efficiency and likely intensified nitrogen deficiency during late vegetative and reproductive phases. At the same time, the faster development observed in S2H1A2 and S3H1A1 mirrors the findings of S. Pradhan *et al.* (2025), who reported that conservation tillage combined with well-designed weed control can simultaneously maintain soil health and reduce the period of critical competition, thereby stabilising crop development trajectories.

Plant density in the present experiment exerted a less pronounced but still detectable influence on the phenological calendar, mainly through interaction with tillage and herbicide background. The slight 1-2-day delay of development at higher density (A2) during later phases is broadly consistent with the observations of B. Dong *et al.* (2024), who showed that increased stand density in mixed cropping systems intensified competition for light and nitrogen and reduced the photosynthetic capacity of lower leaves in maize. J. Cagnola *et al.* (2025) likewise emphasised that modern high-density maize hybrids are physiologically capable of maintaining yield under stronger competition, but this often comes at the cost of altered canopy dynamics and extended grain-filling under stress. In the Polissia experiment, A_2 did not independently change the overall phenological pattern but amplified the negative effect of inadequate weed control under S1H2 and, conversely, reinforced the positive effect of shallow tillage and herbicides in S2H1A2, suggesting that density should be considered primarily as a fine-tuning tool within an already optimised tillage – weed management framework.

The statistically significant interaction between soil tillage system and herbicide background (F1 × F3) across almost all phenological phases mirrors findings from other cropping systems that emphasise the interdependence of soil physical environment and weed control strategies. K. Jankowski *et al.* (2024) showed in winter oilseed rape that the efficiency of weed management and nutrient use was strongly conditioned by the chosen tillage system, with conservation practices improving the synchrony between crop demand and resource availability. T. Fedoniuk *et al.* (2025) demonstrated, using remote sensing methods in maize fields of Ukraine, that higher weed infestation was consistently associated with specific tillage patterns and crop management combinations, and that integrated systems reduced both weed pressure and spatial variability in crop development. In the current experiment, the sharp contrast between S3H1 and S1H2 in terms of timing of tube emergence, tassel emergence and full ripeness indicates that the same herbicide regimen can produce very different developmental outcomes depending on the underlying soil structure and moisture regime shaped by tillage.

The regression model developed in this study, which explained 71% of the variance in time to FullRip, further supports the view that maize phenology is governed by an integrated set of technological and biotic drivers rather than by single factors acting in isolation. The additive delays associated with the transition from minimal to deep tillage, omission of herbicides, increased disease incidence and higher pest density are consistent with the broader evidence that suboptimal management at the soil, weed and plant protection levels cumulatively shifts critical phenological boundaries into less favourable calendar windows (Vâtcă *et al.*, 2021; Kumar *et al.,* 2025; Mahajan *et al.,* 2025). At the same time, the relatively modest impact of density compared with tillage and herbicides supports the conclusions of Z. Cao *et al.* (2024), who argued that sowing date, thermal environment and soil–water interactions usually exert a stronger influence on maize phenology than stand density per se.

Taken together, the comparative analysis indicates that the Polissia results are congruent with contemporary international and regional studies on maize phenology, conservation tillage and weed management, but they also reveal specific features of gleyic Albic Luvisols under a slightly continental climate. The data confirm that minimal and shallow tillage, when combined with effective herbicide-based weed control, can significantly accelerate the progression of phenological phases and shorten the vegetation period, while high weed pressure and deep ploughing in moisture-variable conditions prolong development and potentially expose crops to less favourable late-season weather. These findings reinforce current recommendations to prioritise integrated optimisation of tillage and weed management as a central element of sustainable maize production strategies in the Polissia zone of Ukraine, with plant density used as a secondary lever to adjust canopy structure within this optimised technological framework.

CONCLUSIONS

The conducted field experiment established that, under the slightly continental, moisture-variable conditions of the Polissia region, maize phenological development is primarily controlled by the soil tillage system, with herbicide background acting as a co-dominant factor and plant density playing a secondary, modifying role. Minimal and shallow tillage (discing and rotary tillage) shortened the duration of individual phenological phases and the overall vegetation period by 2-5 days compared with deep ploughing, particularly from the 7th leaf stage to full ripeness, which indicates that conservation-type tillage creates a more favourable hydrothermal regime on gleyic Albic Luvisols. Herbicide-free variants were characterised by a systematic delay of the ThrowPanic-FullRip interval by 6-10 days, confirming that weed competition substantially slows the transition to generative stages and prolongs grain filling, especially when combined with deep tillage and increased plant density. The most favourable technological combination for rapid phase progression and potentially higher yield was S2H1A2 (discing to 10-12 cm, standard herbicide scheme, density 1.3 seed units ha^{-1}), whereas the slowest development occurred in S1H2A2 (deep ploughing without herbicides and increased density), which formed the longest vegetation period and the latest calendar timing of reproductive phases. Plant density did not significantly change the timing of phases on its own, but enhanced either positive or negative effects of tillage-herbicide combinations, acting mainly through modification of competitive relationships within the crop-weed complex. The statistically significant F1 × F3 interaction across almost all phases and the regression model with $R^2 = 0.71$, which quantified the additive impact of tillage system, herbicide omission, disease incidence and pest density on time to FullRip, demonstrate that maize development is determined by an integrated set of technological and biotic drivers. In practical terms, the results justify a regional strategy focused on the transition to minimal or shallow tillage combined with reliable herbicide-based weed control in order to accelerate development, shorten the vegetation period and enhance agrobiological resilience and productivity of maize in the Polissia zone, while prospects for further research involve assessing the long-term effects of these technological combinations on yield stability, soil quality and weed community dynamics under climate variability.

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REFERENCES

[1] Bezvershuck, I., & Fedoniuk, T. (2025). Sustainable weeds management in maize cultivation: Evaluating agroecological practices and tillage systems. *Scientific Horizons,* 28(7), 22-33. doi: 10.48077/scihor7.2025.22.

[2] Cagnola, J.I., Rotili, D.H., Otegui, M.E., & Casal, J.J. (2025). 50 years of breeding to improve yield: How maize stands up to climate change. *Philosophical Transactions of the Royal Society B,* 380(1927), article number 20240250. doi: 10.1098/rstb.2024.0250.

[3] Cao, Z.Y., Chen, Z.H., Tang, B., Zeng, Q., Guo, H.L., Huang, W.H., Luo, Y., Shen, S., & Zhou, S.L. (2024). The effects of sowing date on maize: Phenology, morphology, and yield formation in a hot subtropical monsoon region. *Field Crops Research,* 309, article number 109309. doi: 10.1016/j.fcr.2024.109309.

[4] Convention on Biological Diversity. (1992, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_030#Text.

[5] Dixit, M., Ghoshal, D., Kumar, S., & Dutta, D. (2024). Enhancing agriculture through strategic tillage and soil management: Unleashing potential for sustainable farming. In *Strategic tillage and soil management – new perspectives*. IntechOpen. doi: 10.5772/intechopen.113038.

[6] Dong, B., Wang, Z., Evers, J.B., Stomph, T.J., van der Putten, P.E., Yin, X., Wang, J.L., Sprangers, T., Hang, X., & van der Werf, W. (2024). Competition for light and nitrogen with an earlier-sown species negatively affects leaf traits and leaf photosynthetic capacity of maize in relay intercropping. *European Journal of Agronomy,* 155, article number 127119. doi: 10.1016/j.eja.2024.127119.

[7] DSTU 4289:2004. (2005). *Soil quality. Methods for determining organic matter*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=56400.

[8] DSTU 4730:2007. (2008). *Soil quality. Determination of particle size distribution using the pipette method modified by N.A. Kachinsky.* Retrieved from https://online.budstandart.com/ua/catalog/doc-page?id_doc=95597.

[9] DSTU ISO 11272-2001. (2002). *Soil quality. Determination of dry mass density (ISO 11272:1998, IDT).* Retrieved from https://online.budstandart.com/ua/catalog/doc-page?id_doc=58941.

[10] Fedoniuk, T., Zhuravel, S., Kravchuk, M., Pazych, V., & Bezvershuck, I. (2024). Historical sketch and current state of weed diversity in continental zone of Ukraine. *Agriculture and Natural Resources,* 58(5), 631-642. doi: 10.34044/j.anres.2024.58.5.10.

[11] Fedoniuk, T.P., Pyvovar, P.V., Topolnytskyi, P.P., Rozhkov, O.O., Kravchuk, M.M., Skydan, O.V., Pazych, V.M., & Petruk, T.V. (2025b). Utilizing remote sensing data to ascertain weed infestation levels in maize fields. *Agriculture,* 15(7), article number 711. doi: 10.3390/agriculture15070711.

[12] Huang, S.S., Islam, M.U., & Jiang, F.H. (2023). The effect of deep-tillage depths on crop yield: A global meta-analysis. *Plant, Soil and Environment,* 69, 105-117. doi: 10.17221/373/2022-PSE.

[13] IUSS Working Group WRB. (2022). Retrieved from https://wrb.isric.org/.

[14] Jankowski, K.J., Sokólski, M., Szatkowski, A., & Załuski, D. (2024). The effects of tillage systems on the management of agronomic factors in winter oilseed rape cultivation: A case study in north-eastern Poland. *Agronomy,* 14(3), article number 437. doi: 10.3390/agronomy14030437.

[15] Kumar, S., *et al.* (2025). Dual-stage herbicide regimen for tackling weed menace in wheat under multiple crop establishment systems. *Frontiers in Sustainable Food Systems,* 9, article number 1624283. doi: 10.3389/fsufs.2025.1624283.

[16] Mahajan, S., Thakur, P., Das, S., Sharma, R.P., Manuja, S., Jha, P.K., Saini, A., Sahoo, Ch., & Fayezizadeh, M.R. (2025). Impression of contemporary heat stress complexities in agricultural crops: A review. *Plant Growth Regulation*. doi: 10.1007/s10725-025-01382-8.

[17] Molina-Herrera, F.I., Jiménez-Islas, H., Sandoval-Hernández, M.A., Maldonado-Sierra, N.E., Domínguez Campos, C., Jarquín Enríquez, L., Mondragón Rojas, F.J., & Flores-Martínez, N.L. (2025). Modeling temperature and moisture dynamics in corn storage silos with and without aeration periods in three dimensions. *ChemEngineering,* 9(4), article number 89. doi: 10.3390/chemengineering9040089.

[18] Naruhn, G.P., Hartung, J., Schulz, V., Möller, K., & Gerhards, R. (2025). How equal space seeding in maize (*Zea mays* L.) influences weed competition, crop growth, and grain yield. *Crop Science,* 65(5), article number e70152. doi: 10.1002/csc2.70152.

[19] Nedeljković, D., Božić, D., Malidža, G., Rajković, M., Knežević, S.Z., & Vrbničanin, S. (2025). Influence of time of weed removal on maize yield and yield components based on different planting patterns, pre-emergence herbicides, and weather conditions. *Plants,* 14(3), article number 419. doi: 10.3390/plants14030419.

[20] Pradhan, S., Garnayak, L.M., Dash, R., Behera, R.D., Bharteey, P.K., Dandasena, S., Priyadarshini, S., Hazarika, N., Hussain, S., Borah, S.R., Rai, S., Pandey, S., & Gupta, R. (2025). Innovative conservation tillage and weed management techniques under rice-maize-cowpea system for higher productivity, resource use efficiency and healthy soil in coastal Odisha. *Plant Science Today,* 12(sp4), 01-10. doi: 10.14719/pst.9984.

[21] Savić, A., Popović, A., Đurović, S., Pisinov, B., Ugrinović, M., & Todorović, M.J. (2025). A framework for understanding crop-weed competition in agroecosystems. *Agronomy*, 15(10), article number 2366. doi: 10.3390/agronomy15102366.

[22] Shevchenko, S., Derevenets-Shevchenko, K., Desyatnyk, L., Shevchenko, M., Sologub, I., & Shevchenko, O. (2024). Tillage effects on soil physical properties and maize phenology. *International Journal of Environmental Studies,* 81(1), 393-402. doi: 10.1080/00207233.2024.2320032.

[23] Shi, X., Li, C., Li, P., Zong, Y., Zhang, D., Gao, Z., Hao, X., Wang, J., & Lam, S.K. (2024). Deep plowing increases soil water storage and wheat yield in a semiarid region of the Loess Plateau in China: A simulation study. *Field Crops Research,* 308, article number 109299. doi: 10.1016/j.fcr.2024.109299.
[24] Skydan, O.V., Dankevych, V.Y., Fedoniuk, T.P., Dankevych, Y.M., & Yaremova, M.I. (2022). European Green Deal: Experience of food safety for Ukraine. *International Journal of Advanced and Applied Sciences*, 9(2), 63-71. doi: 10.21833/ijaas.2022.02.007.
[25] Vâtcă, S.D., *et al.* (2021). Agrometeorological requirements of maize crop phenology for sustainable cropping: A historical review for Romania. *Sustainability,* 13(14), article number 7719. doi: 10.3390/su13147719.

Вплив агротехнологічних факторів на швидкість розвитку та проходження фенологічних фаз кукурудзи (*Zea mays* L.)

Ігор Безвершук
Аспірант
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0009-0007-8081-9815

Анотація. Метою дослідження було визначення впливу системи основного обробітку ґрунту, густоти стояння рослин та гербіцидного фону на швидкість фенологічного розвитку кукурудзи за континентальних кліматичних умов Поліської зони України. Польовий дослід проводився протягом 2023–2025 рр. і охоплював три системи обробітку ґрунту (глибока оранка, дискування та ротарний обробіток), два рівні густоти рослин (1,1 і 1,3 посівних одиниці на 1 га) та два варіанти гербіцидного фону (із застосуванням і без застосування гербіцидів), розміщені у трифакторній схемі з трьома повтореннями. Фенологічні фази (від SeedGerm до FullRip) реєструвалися за календарними датами їх настання. Статистичну обробку здійснювали з використанням дисперсійного аналізу (ANOVA), регресійного моделювання та порівняння скоригованих середніх. Встановлено, що система обробітку ґрунту була домінувальним фактором, який визначав швидкість розвитку кукурудзи. Мінімальний і мілкий обробіток прискорював проходження фенологічних фаз на 2–5 діб порівняно з глибокою оранкою. Гербіцидний фон мав вирішальний вплив на середні та пізні етапи розвитку: за відсутності гербіцидів тривалість інтервалу ThrowPanic–FullRip зростала на 6–10 діб унаслідок посилення конкуренції з боку бур'янів. Взаємодія факторів F1 × F3 була статистично значущою в більшості фаз і визначала загальний темп розвитку. Вплив густоти стояння рослин мав другорядний характер і проявлявся переважно через її взаємодію з гербіцидним фоном. Найшвидший розвиток відмічався у варіанті S3H1A2 (ротарний обробіток, застосування гербіцидів, підвищена густота), тоді як найповільніший – у S1H2A2 (глибока оранка, відсутність гербіцидів, підвищена густота). Зроблено висновок, що оптимізація системи обробітку ґрунту в поєднанні з ефективним контролем бур'янів є ключовою умовою прискорення розвитку кукурудзи та забезпечення стабільної продуктивності в Поліській зоні. Мінімальний обробіток у поєднанні з гербіцидним захистом може рекомендуватися як найефективніша стратегія для підвищення темпів росту, скорочення вегетаційного періоду та посилення агробіологічної стійкості кукурудзи в регіональних умовах

Ключові слова: фенологічний розвиток; система обробітку ґрунту; гербіцидний фон; конкуренція з бур'янами; густота стояння рослин