Bulgarian Journal of Agricultural Science, 32 (No 5) 2026, 1002–1010

DOI: https://doi.org/10.61308/SRGF7962

Agroecological potential of einkorn (*Triticum monococcum* L.) in conventional, organic and biodynamic farming systems

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Abstract

Maneva, V., Atanasova, D., Chipilski, R. & Bozhanova, V. (2026). Agroecological potential of einkorn (*Triticum monococcum* L.) in conventional, organic and biodynamic farming systems. *Bulg. J. Agric. Sci., 32*(5), 1002–1010

The agroecological potential of einkorn (*Triticum monococcum* L.) was evaluated under three farming systems – conventional, organic, and biodynamic, over two contrasting growing seasons (2020–2022) in Southeastern Bulgaria. The study assessed the physiological plasticity, yield components, and natural resistance to the cereal aphid *Sitobion avenae*. Results indicated that while the conventional system showed higher photosynthetic rates and spike length under favorable conditions, the organic and biodynamic systems exhibited superior resilience during drought. Biodynamic farming consistently achieved the highest instantaneous water-use efficiency (iWUE), increasing from 5.57 in 2021 to 6.48 in 2022, and maintained significantly higher thousand kernel weight (TKW) (33.00–36.35 g). Yield dynamics revealed that under stress, the organic system outperformed the conventional one, which suffered a 28% yield decline. Aphid infestation remained well below the economic threshold across all cultivation systems, with the lowest densities recorded in biodynamic and organic plots. These findings position einkorn as a strategic crop for agroecological intensification, capable of sustaining stable yields and enhancing ecological regulation under climate variability.

Keywords: Einkorn (*Triticum monococcum* L.); farming systems; physiological plasticity; water-use efficiency; yield resilience

Introduction

The urgent need for sustainable cereal production is reinforced by escalating challenges such as climate variability, soil degradation, and biodiversity decline (FAO, 2020; IPCC, 2022). In this context, ancient hulled wheat species like einkorn (*Triticum monococcum* L.) are attracting growing interest due to their genetic diversity, low-input adaptability, and exceptional nutritional value (Zaharieva et al., 2010; Damyanova, 2016; Gálová et al., 2021). Bulgarian studies also confirm einkorn's resilience under less intensive farming systems (Atanasova and Maneva, 2024; Maneva et al., 2019).

Despite its adaptive advantages, the physiological and agronomic responses of einkorn to different agricultural systems remain under-researched, particularly under organic and biodynamic conditions. The conventional cereal production, while still predominant, is associated with environmental externalities such as soil nutrient depletion, reduced microbial diversity, and greater susceptibility to pests (Tilman et al., 2002; Pretty and Bharucha, 2014). In contrast, organic and biodynamic systems emphasize soil regeneration, natural pest regulation, and sustainable crop productivity (Reganold and Wachter, 2016; Heller et al., 2022; Raupp and König, 2017). Biodynamic agriculture, in particular, utilizes

specific composts and preparations (e.g., BD 502–507), and has shown potential in promoting plant resilience and improving soil microbiome function (Atanasova and Maneva, 2024; Maneva et al., 2019).

Plant development and yield components such as spike length, grain number per spike, grain weight, and thousand kernel weight (TKW), are strongly influenced by both physiological efficiency and environmental conditions. Key indicators like photosynthetic rate, stomatal conductance, and instantaneous water use efficiency (iWUE) are important for evaluating crop responses to management systems (Nawaz et al., 2020; Poudel et al., 2021; Olesen and Børgesen, 2021). Recent work under Bulgarian field conditions confirms that biodynamic and organic management can sustain photosynthetic activity and yield under drought stress (Atanasova and Maneva, 2024; Maneva et al., 2019).

Pests' dynamics also differs markedly across systems. Aphids, particularly Sitobion avenae, are economically significant pests in wheat that impair yield via phloem feeding and virus transmission (Van Emden and Harrington, 2017; Evans et al., 2020). Their population levels are sensitive to agronomic practices – especially nitrogen fertilization and habitat structure (Birkhofer et al., 2008). Biodynamic and organic fields often support richer natural enemy assemblages and show lower aphid pressure (Garratt et al., 2010; Hristov et al., 2022).

The present study aims to make a comparative analysis of the agroecological efficiency of three agricultural systems (conventional, organic and biodynamic) by assessing the physiological plasticity, structural components of yield and natural resistance to aphids (*Sitobion avenae*) in einkorn wheat (*Triticum monococcum* L.) in the conditions of Southeastern Bulgaria.

Materials and Methods

Experimental setup and growth conditions

A field experiment was conducted at the experimental fields of the Institute of Agriculture – Karnobat, over the two growing seasons (2020–2022). Plots of einkorn (*Triticum monococcum* L.) with an area of 500 m² were established under three different farming systems – conventional, organic, and biodynamic**,** each replicated four times.

In the conventional system**,** einkorn was cultivated with the application of synthetic nitrogen fertilizers and pesticides (Florasulam + Tritosulfuron; Fenoxaprop – P-ethyl; Epoxiconazole + Pyraclostrobin and Cypermethrin, applied at recommended doses). In the organic system**,** cattle manure was incorporated at a rate of 50–60 t/ha without the use of pesticides. In the biodynamic system, biodynamic compost prepared from cow manure enriched with standard biodynamic preparations (BD 502, 503, 504, 505, 506, and 507) was applied at a rate of 5–6 t/ha, with no synthetic fertilizers or pesticides.

After crop maturity, plant samples were collected by cutting 1-meter-long rows from each plot. Biometric measurements were conducted, and grain yield was determined for each farming system.

Aphid infestation observations were performed directly on plants at 10 randomly selected locations. For each treatment and replicate, 10 wheat stems were examined per site. The mean values from the four replicates were used for statistical analysis.

Physiological measurements

Leaf gas exchange parameters were measured using a portable intelligent photosynthesis system LCpro+ Ti (Opti Sciences, USA) over two consecutive growing seasons. Intact flag leaves from each treatment were selected to determine: photosynthetic assimilation rate (A), transpiration rate (E), intercellular (substomatal) CO_2 concentration (Ci) and stomatal conductance (Gs).

Instantaneous water-use efficiency (iWUE) was calculated as the ratio A/E.

Measurements were taken at the medium milk stage of grain development (Zadoks growth stage 75), using the middle section of the leaf blade. Data were collected between 09:00 and 11:00 AM.

Environmental conditions in the measurement chamber were as follows: Air temperature: 25.4–26.4°C and 26.5–28.3°C; Relative humidity: 16.8–17.8 mbar and 13.7–15.0 mbar; Photosynthetically active radiation (PAR): 699–1100 µmol $m^{-2}s^{-1}$ and 1300–1700 µmol $m^{-2}s^{-1}$; Ambient CO_2 concentration: 385–395 ppm and 405–418 ppm.

Statistical methods

The obtained results were statistically analyzed by calculating the standard deviation (SD), and performing one-way and two-way analysis of variance (ANOVA), followed by the least significant difference (LSD) test to evaluate differences between mean values. Statistical analyses were performed using SPSS 24 (IBM).

Agrometeorological overview of the study period

The analysis revealed substantial differences in the agrometeorological conditions between the two years of the study. While an overall increase in air temperatures was observed, the moisture regimes were sharply contrasting: precipitation in the first year significantly exceeded the long-term average, while the second year was marked by severe

deficits, particularly during critical growth stages (Table 1).

The 2020/2021 season featured monthly temperatures exceeding the long-term average by total of +2.1°C. From a statistical perspective, the deviations in December and January were more than double the standard deviation (1.6–2.0) (calculated using Microsoft Excel), marking this overwintering period as exceptionally warm. The first autumn frost in the Karnobat region occurred on November 1, 2020, and the last spring frost was recorded on May 12, 2021. Total precipitation reached 691.88 *mm*, which is 21% above the multiannual average. While generally favorable for soil moisture recovery, the distribution was highly irregular. January recorded 142.8 *mm*. This deviation of +106.3 *mm* represents a statistically significant outlier, explaining the excess soil moisture that hampered successful overwintering. Cool and wet conditions in March and April delayed crop development. Specifically, April rains provided vital moisture for stem elongation, heading and milk ripeness. Heavy rainfall in late June and early July (+52.2 *mm* above the June norm) complicated harvesting operations (Table 1).

During the 2021/2022 season, precipitation became the main limiting factor. Total rainfall was 13% lower than the long-term norm and unevenly distributed. Precipitation in January, March and July fell drastically below average. July recorded only 2.7 *mm* of rain against a norm of 49.9 *mm* – a deficit of -47.2 *mm*. The accumulated heat sum (October – June) exceeded the norm by 193.6°C. Combined with air humidity levels that were 7.4 % lower than average for 9 out of 12 months, this created significant stress for crop development (Table 1).

As a result of meteorological variability, cereal crops developed under distinctly contrasting conditions. The statistical variability of precipitation in the first year (characterized by a high winter standard deviation), in contrast to prolonged drought in the second year, was a decisive factor influencing crop development and yield formation.

Results

Analysis of physiological measurements in einkorn

The results from the two years of study show significant differences depending on the farming system applied (conventional, organic, and biodynamic) as well as the climatic conditions (Table 2).

During the favorable year of 2021, significant differences were observed in the rates of photosynthetic assimilation (A) and transpiration (E) among the three systems. The conventional system exhibited the highest levels of photosynthesis (6.73 ± 0.32) and transpiration (1.31 ± 0.04). The organic and biodynamic systems showed significantly lower levels of photosynthesis compared to the conventional system in the first year (4.01 ± 0.59 for organic and 2.52 ± 0.45 for biodynamic). In the dry year of 2022, the values of A and E decreased sharply across all systems. However, the organic system maintained the highest photosynthetic intensity (2.78 ± 0.37), suggesting better adaptability to stress compared to the conventional system (2.08 ± 0.25).

Stomatal conductance (Gs) is a key indicator of plant water status. In 2021, the biodynamic system maintained significantly lower stomatal conductance (0.029 ± 0.003) compared to the conventional (0.076 ± 0.004) and organic systems (0.067 ± 0.008). In the dry year of 2022, all values were very low, with no differences observed among the farming systems. Data from both years indicate that the biodynamic system maintains lower stomatal conductance (Gs), which limits water loss.

Intercellular CO_2 concentration (Ci) was higher in the organic (277.4 ± 11.47) and biodynamic (272.3 ± 19.96) systems in 2021 compared to the conventional system (214.5 ± 6.75). The similar Ci values in the organic and biodynamic systems indicate that, in both cases, plants did not experience a shortage of carbon dioxide in the leaf mesophyll. In 2022, the mean values did not differ significantly between

Table 1. Agro-meteorological conditions during the study period

Parameter	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Temperature													
Perennial (°C)	12.5	7.1	2.6	0.6	2.2	5.3	10.5	15.6	19.6	22.0	21.6	17.6	11.4
2020/2021 (°C)	15.8	7.4	6.6	3.7	4.9	4.9	9.5	16.6	19.3	24.1	23.7	19.1	13.0
2021/2022 (°C)	11.1	8.7	4.5	2.4	4.4	3.5	11.2	15.9	21.0	23.4	24.6	18.8	12.5
SD	2.5	0.8	2.0	1.6	1.4	1.0	0.9	0.5	0.9	1.1	1.5	0.9	
Precipitation													
Perennial (*mm*)	44.3	53.7	51.2	36.5	35.8	34.1	45.3	58.5	65.2	49.9	33.7	40.8	550.0
2020/2021 (°C)	70.7	25.5	94.5	142.8	22.1	47.4	86.0	15.6	117.4	34.9	15.6	19.3	691.8
2021/2022 (*mm*)	79.1	31.7	105.7	8.0	39.7	11.7	47.8	36.3	86.8	2.7	17.3	11.4	478.5
SD	19.1	15.1	29.7	10.6	9.5	19.5	21.8	21.8	26.1	24.5	9.3	14.8	

Source: Authors' own elaboration

Table 2. Physiological measurements in einkorn (2021– 2022)

Farming system	A µmol m^{-2} s^{-1}	E mmol m^{-2} s^{-1}	Ci vpm	Gs mmol m^{-2} s^{-1}	iWUE ration
2021					
Conventional farming	6.73 ± 0.32 [a]	1.31 ± 0.04 [a]	214.5 ± 6.75 [b]	0.076 ± 0.004 [a]	5.12 ± 0.45 [ab]
Organic farming	4.01 ± 0.59 [b]	0.89 ± 0.10 [b]	277.4 ± 11.47 [a]	0.067 ± 0.008 [a]	4.35 ± 0.25 [b]
Biodynamic farming	2.52 ± 0.45 [c]	0.44 ± 0.02 [c]	272.3 ± 19.96 [a]	0.029 ± 0.003 [b]	5.57 ± 0.35 [a]
LSD 5 %	1.17	0.16	24.3	0.014	0.79
2022					
Conventional farming	2.08 ± 0.25 [ab]	0.62 ± 0.03 [a]	183.0 ± 17.22 [a]	0.017 ± 0.002 [a]	3.31 ± 0.38 [c]
Organic farming	2.78 ± 0.37 [a]	0.56 ± 0.07 [a]	149.8 ± 11.51 [a]	0.018 ± 0.003 [a]	4.92 ± 0.41 [b]
Biodynamic farming	1.78 ± 0.17 [b]	0.28 ± 0.03 [b]	167.3 ± 23.20 [a]	0.013 ± 0.002 [a]	6.48 ± 0.29 [a]
LSD 5 %	0.88	0.16	46.38	0.007	0.89
Average values 2021–2022					
Conventional farming	4.41 [a]	0.97 [a]	198.8 [a]	0.047 [a]	4.22 [b]
Organic farming	3.40 [a]	0.73 [b]	213.6 [a]	0.043 [a]	4.64 [b]
Biodynamic farming	2.15 [b]	0.36 [c]	219.8 [a]	0.021 [b]	6.03 [a]
LSD 5 %	1.17	0.19	39.7	0.018	0.69

A – CO_2 Photosynthetic Assimilation Rate; E – H_2O Transpiration Rate; Ci – Intercellular (Sub-stomatal) CO_2 Concentration; Gs – Stomatal Conductance; iWUE (A/E) – Instantaneous Water Use Efficiency.

Means that share a letter do not differ significantly at $p < 0.05$.

Source: Authors' own elaboration

the farming systems.

The indicator iWUE (A/E ratio – instantaneous water use efficiency) is critical for assessing drought tolerance. Biodynamic farming showed the highest and progressively increasing iWUE values – from 5.57 in 2021 to 6.48 in 2022. This is due to the maintenance of low transpiration with relatively stable assimilation. While water use efficiency in the conventional system decreased significantly in 2022 (from 5.12 to 3.31), the organic and biodynamic systems maintained their efficiency.

The data show that the conventional system relies on high intensity when conditions are favorable, whereas the organic and biodynamic systems operate with lower energy input and perform better under stress conditions.

Analysis of yield components under different farming systems

The agronomic characteristics of einkorn also reflect significant differences among the farming systems (Table 3). Organic and biodynamic farming show a higher potential for the formation of productive tillers in einkorn. In 2021, the highest values were recorded under biodynamic farming (617 nb/m^2), while in 2022, although the highest mean was scored for the organic management (651 nb/m^2), it was not statistically different from the biodynamic system (634 nb/m^2) (Table 3). Biodynamic farming demonstrated competitive and high values for spike length in 2021, which may be associated with better development of generative organs. Despite the overall decline in 2022, the values remained relatively stable. Indicators related to the spike (length and number of kernels) were more favorable under conventional farming, whereas grain quality, expressed as thousand kernel weight (TKW), was consistently higher in biodynamic treatments (36.35 g in 2021 and 33.00 g in 2022).

The farming system had a significant effect on spike length ($F = 49.12$, $p < 0.001$), with the highest values in both 2021 and 2022 observed under conventional farming and the lowest under organic farming in 2021 and biodynamic farming in 2022. In 2022, a general decrease in values was observed. The "year" factor also had a statistically significant effect ($F = 61.23$, $p < 0.001$). The interaction between factors ($F = 25.89$, $p < 0.001$) indicates that plant responses to different farming systems depend on the specific environmental conditions.

The results show that the cultivation system significantly affects the number of kernels per spike ($F = 48.73$, $p < 0.001$), with the highest values observed under conventional farming and the lowest under organic farming. The "year" factor had a very strong influence ($F = 146.87$, $p < 0.001$), with a marked decrease in kernel number observed in 2022.

Biodynamic farming was characterized by the highest values of thousand kernel weight (TKW) in both years, indicating more complete grain filling and better product quality. The "year" factor had a very strong effect on TKW ($F = 1266.27$, $p < 0.001$), with a clearly expressed decrease in grain weight across all farming systems in 2022. The high-

est values were again recorded under biodynamic farming. The interaction between factors was statistically significant (F = 3.91, p = 0.039), but with a weaker effect compared to the main factor.

Analysis of grain yield under different farming systems

The results demonstrate a clear influence of the farming system on einkorn yield, with distinct responses depending on environmental conditions (Table 4).

In the first year, characterized by favorable conditions, the biodynamic system achieved the highest yield (3.72 t/ha), followed closely by the conventional system (3.59 t/ha), while the organic system reported the lowest yield (3.20 t/ha). This pattern suggests that under optimal conditions, systems with higher or more balanced nutrient availability – such as biodynamic and conventional – can better realize yield potential.

During the second year, the biodynamic (4.06 t/ha) and organic (3.90 t/ha) systems achieved similarly high yields and did not differ significantly from each other, whereas the conventional system produced significantly lower yields (2.58 t/ha).

The analysis of variance supports these observations (Table 5). The factor "system" had a highly significant effect on yield (F = 12.384, p = 0.0004), confirming that the choice of farming system is a key determinant of productivity. In contrast, the main effect of "year" was not statistically significant (F = 0.518, p = 0.481), suggesting that interannual variability alone does not fully explain yield differences. However, the interaction between year and system was highly significant (F = 12.791, p = 0.0003), indicating that the performance of each farming system strongly depends on the specific environmental conditions of the given year.

These findings confirm that low-input systems can ensure stable and competitive productivity under variable climatic conditions, supporting evidence that organic and biodynamic management buffer environmental stress and enhance yield resilience (Atanasova and Maneva, 2024; Heller et al., 2022).

Analysis of aphid infestation dynamics on einkorn under three farming systems

During the 2021 growing season, aphid infestation in einkorn remained at low levels in all three systems tested. The peak infestation in the conventional system reached only 3 aphids per 100 stems, while an even lower density of 1 aphid per 100 stems was recorded in the biological system.

In the first year of the study (2021), a clear peak in *Sitobion avenae* population density was observed. This maximum was recorded between the late April and the early May, with

Table 4. Grain yield in einkorn

Farming system	2021	2022	Average values (2021–2022)
Conventional farming	3.59 ± 0.10^{a}	2.58 ± 0.39^{b}	3.09 ± 0.60^{b}
Organic farming	3.20 ± 0.09^{b}	3.90 ± 0.17^{a}	3.55 ± 0.40^{a}
Biodynamic farming	3.72 ± 0.16^{a}	4.06 ± 0.38^{a}	3.89 ± 0.32^{a}
LSD 0.05 %	0.19	0.49	0.33

Means that share a letter do not differ significantly at p < 0.05.
Source: Authors' own elaboration

Table 3. Yield components in einkorn (2021–2022)

Farming system	Productivity tillering (PT)	Plant height (H)	Spike length (SL)	Number of kernels per spike (NKS)	Kernels weight per spike (KWS)	Thousand kernel weight (TKW)
2021						
Conventional farming	549 ± 18.73 ^{b}	97.50 ± 4.70 ^{a}	5.43 ± 0.05 ^{a}	21.35 ± 0.87 ^{a}	0.66 ± 0.04 ^{a}	33.50 ± 0.22 ^{b}
Organic farming	551 ± 19.29 ^{b}	100.08 ± 1.00 ^{a}	4.95 ± 0.05 ^{b}	17.55 ± 0.40 ^{c}	0.48 ± 0.02 ^{b}	32.88 ± 0.04 ^{b}
Biodynamic farming	617 ± 16.97 ^{a}	86.95 ± 0.85^{b}	5.28 ± 0.08 ^{c}	19.13 ± 0.26 ^{b}	0.60 ± 0.05 ^{a}	36.35 ± 0.05 ^{a}
LSD 0.05 %	43.6	5.08	0.11	1.01	0.07	0.25
2022						
Conventional farming	476 ± 20.30 ^{b}	113.03 ± 4.67 ^{a}	5.08 ± 0.08 ^{a}	17.45 ± 0.29 ^{a}	0.54 ± 0.04 ^{a}	30.23 ± 0.24 ^{b}
Organic farming	651 ± 17.78 ^{a}	104.98 ± 0.77 ^{b}	4.63 ± 0.13 ^{b}	16.13 ± 0.69 ^{ab}	0.51 ± 0.05 ^{a}	29.60 ± 0.14 ^{c}
Biodynamic farming	624 ± 36.49 ^{a}	95.23 ± 0.42 ^{c}	4.25 ± 0.11 ^{c}	15.45 ± 1.66 ^{b}	0.48 ± 0.05 ^{a}	33.00 ± 0.35 ^{a}
LSD 0.05 %	43.6	4.93	0.19	1.86	0.09	0.46
Average values 2021–2022						
Conventional farming	512.50 ± 44.59 ^{b}	105.26 ± 9.47 ^{a}	5.26 ± 0.21 ^{a}	19.40 ± 2.13 ^{a}	0.60 ± 0.07 ^{a}	31.87 ± 1.76 ^{b}
Organic farming	601.00 ± 58.74 ^{a}	102.53 ± 2.85 ^{a}	4.79 ± 0.20 ^{b}	16.84 ± 0.99 ^{b}	0.49 ± 0.04 ^{b}	31.24 ± 1.68 ^{b}
Biodynamic farming	620.50 ± 31.07 ^{a}	91.09 ± 4.41 ^{b}	4.76 ± 0.56 ^{b}	17.29 ± 2.37 ^{b}	0.54 ± 0.08 ^{ab}	34.68 ± 1.77 ^{a}
LSD 0.05 %	48.24	6.16	0.37	2.00	0.07	1.81

Means that share a letter do not differ significantly at p < 0.05.
Source: Authors' own elaboration

Table 5. Analysis of variance of grain yield in einkorn

Source	SS	df	MS	F-critical	p-value	Significance
Year	0.052	1	0.052	0.518	0.481	ns
System	2.503	2	1.251	12.384	0.0004	***
Y × S	2.585	2	1.293	12.791	0.0003	***
Error	1.819	18	0.101			

Source: Authors' own elaboration

values, varying significantly depending on the agricultural system used. In none of the tested systems did the population density exceed the economic threshold of 10 aphids per stem. These values indicate that einkorn (*Triticum monococcum*) exhibits a high degree of tolerance or is not a preferred host for mass aphid reproduction. After mid-June, a decrease in numbers was observed in all three systems, which is probably related to the phases of crop maturation and increasing temperatures. The fact that there are fewer aphids in the biological system (0.01 compared to 0.03), and are not observed in the biodynamic system, may be due to the higher biodiversity and the presence of natural enemies, which control the enemy from the very beginning.

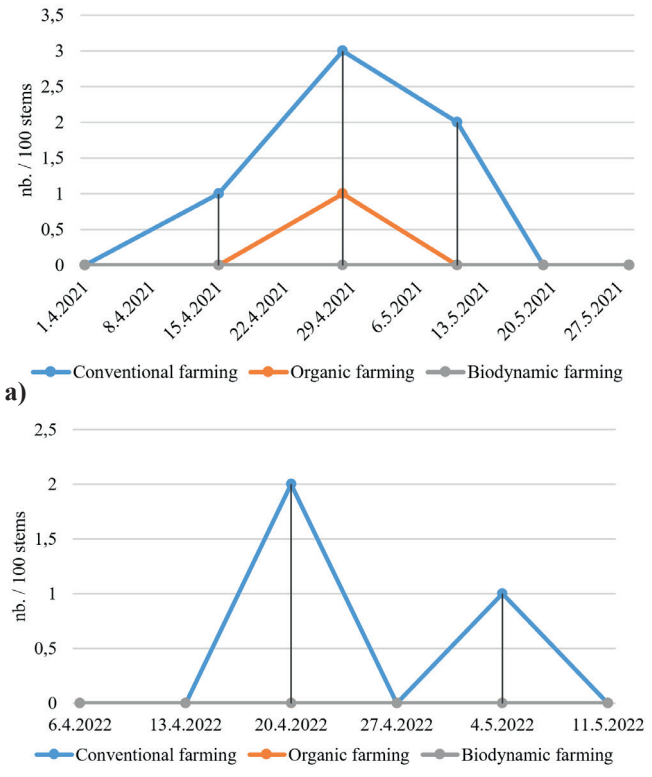


Fig. 1. Numerical dynamics of aphids in three agricultural systems on einkorn (2021–2022)
Source: Authors' own elaboration

In both 2021 and 2022, the *Sitobion avenae* populations reached their highest densities in conventional plots, with peaks observed in late April, whereas organic and biodynamic fields consistently supported significantly lower infestation levels.

The differences between the organic, biodynamic and conventional systems are greatly reduced. However, the conventional system again maintains relatively higher numbers than the other two during the peak period.

Discussion

Our findings confirm that farming system selection plays a decisive role in shaping the physiology, grain productivity, and pest dynamics of einkorn. The physiological responses observed in the two contrasting years reveal a trade-off between productivity at high inputs and resilience at low inputs. The good physiological performance of the conventional system in the favorable year 2021 suggests that when moisture and synthetic nutrients are sufficient, einkorn maximizes its gas exchange capacity to achieve rapid biomass accumulation. Under environmental changes, such as the drought in 2022, and the sharp decline in physiological parameters, it shows that industrial inputs fail to compensate for the effects of climate stress. Organic and biodynamic systems suggest promoting conservative resource management. By limiting water loss, plants conserve soil moisture, which explains the higher iWUE observed in biodynamic farming. Gas regime (Ci) further explains this resilience. While conventional plants suffered from the drought, the stable internal CO_2 concentration in alternative systems indicates that their photosynthetic apparatus remained functional.

The ability of the organic system to maintain the highest photosynthetic intensity under stress confirms that organic management promotes physiological conditioning, allowing the crop to tolerate severe environmental fluctuations. These conservative water use and physiological strategies are consistent with recent studies highlighting improved drought tolerance in organic and biodynamic systems (Nawaz et al., 2020; Poudel et al., 2021; Maneva et al., 2019). Such an ability of both farming systems to optimize internal resources is of particular importance given the projections of increas-

ing drought frequency in Southeastern Europe (Olesen and Børgesen, 2021; Heller et al., 2022).

Agronomic traits responses also demonstrated distinct system-dependent patterns. While conventional management contributes to increased spike length and number of kernels, biodynamic farming improved kernel weight, supporting evidence that soil biological activity and compost-based amendments enhance grain filling and seed vigor (Gálová et al., 2021; Atanasova and Maneva, 2024). Recent reports also show that einkorn expresses superior nutritional and seed quality attributes under low-input management, further confirming its value for agroecological farming (Dinu et al., 2021; Ronga et al., 2023).

Yield dynamics emphasize that organic and biodynamic systems can sustain productivity comparable to or exceeding conventional farming. This finding is consistent with meta-analyses indicating that the yield gap between conventional and organic systems can narrow substantially under stress-prone environments, especially when legumes or compost-based fertilization are integrated (Ponisio et al., 2015; Seufert et al., 2022). For einkorn specifically, the resilience in yield performance highlights its potential as a diversification crop in sustainable cereal rotations (Zaharieva et al., 2010; Damyanova, 2016).

The population dynamics of *Sitobion avenae* highlight the ecological self-regulation inherent in agroecological systems. The most important finding is that aphid densities never exceeded the economic threshold of damage in any system or year. This strongly suggests that *Triticum monococcum* possesses a natural tolerance to the host, possibly due to structural features of the leaves, lower palatability or specialized secondary metabolites that make it an unfavorable host for aphid mass reproduction compared to modern wheats.

However, variations in the microenvironment created by agricultural systems clearly modulate pest pressure:

- Nitrogen hypothesis: The consistently higher aphid peaks in conventional plots in late April and early May point to a classic "luxury consumption" effect, in which synthetic nitrogen fertilizers increase the concentrations of free amino acids in the plant sap, accelerating aphid reproduction.
- Early season suppression: The minimal presence of aphids in organic fields and their complete absence in biodynamic plots during the early season indicate functional biodiversity. Rather than relying on chemical interventions, these systems benefit from richer ecological networks and an established complex of natural enemies (predators and parasitoids) that suppress pest populations from the initial stages of colonization.

The fact that these differences decreased in the dry year of 2022 is likely due to the excessive effect of high temperatures and accelerated crop ripening, which naturally limited the aphid feeding window in all treatments. These field observations are consistent with long-term European experiments where reduced-input and agroecological systems have supported a greater diversity of predators and have successfully mitigated pest risks without the need for synthetic pesticides (Birkhofer et al., 2008; Garratt et al., 2010; Tschumi et al., 2022; Evans et al., 2020; Hristov et al., 2022). Similar findings were reported in long-term European experiments, where reduced-input systems supported higher predator diversity and limited aphid outbreaks (Tschumi et al., 2022; Evans et al., 2020). These results underline the potential of agroecological management to mitigate pest risks while reducing reliance on synthetic pesticides.

Taken together, the integration of physiological, biometric, and pest dynamics assessments positions einkorn as a strategic species for agroecological intensification. By sustaining yields, and enhancing ecological regulation, einkorn under biodynamic and organic management contributes to sustainable cropping systems in the context of climate change and biodiversity conservation. Future studies should expand to multi-location trials, genomic analyses of adaptive traits, and long-term monitoring of soil–plant–insect interactions to consolidate its role in sustainable cereal production.

Conclusions

Based on the presented data and analysis, the following conclusions can be formulated:

The conventional system achieves maximum photosynthetic intensity under favorable conditions, but is highly vulnerable to drought. The biodynamic system exhibits the highest and progressively increasing water use efficiency (iWUE) by maintaining lower stomatal conductance, and the organic system retains the highest photosynthetic activity under stress conditions.

While conventional management promotes higher kernel numbers per spike under optimal conditions, organic and biodynamic systems compensate by having a higher potential for producing productive siblings. Biodynamic production also ensures consistently higher 1000 kernel weight (TKW), which guarantees better grain filling.

The choice of farming system and its interaction with the climatic conditions of the year are decisive for productivity ($p < 0.001$). During drought, the conventional system suffers a critical yield collapse (by about 28%), while the organic and biodynamic systems demonstrate a buffering effect and achieve higher and more stable productivity in a stressful environment.

Einkorn (*Triticum monococcum*) has a high natural tolerance to aphids (*Sitobion avenae*), with no system exceeding the economic threshold. Pest density is highest under conventional management (due to the stimulating effect of synthetic nitrogen), while organic and biodynamic systems suppress the attack early in the season thanks to higher biodiversity and natural enemies.

The integration of high physiological plasticity and low susceptibility to pests makes einkorn a vital component for sustainable cereal rotations. The study supports the wider adoption of organic and biodynamic practices to mitigate climate change risks and reduce reliance on synthetic inputs in cereal production.

Funding

This research was funded by project BG16RFPR002-1.014-0012-C01 „Establishment and sustainable development of a Center of Competence „Agrifood Systems and Bioeconomy", financed by the European Regional Development Fund through the „Program for Research, Innovation and Digitalisation for Smart Transformation"(PRIDST).

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Received: **February, 16, 2026**; *Approved*: **June, 19, 2026**; *Published*: **October, 2026**