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Ancient Wheat Species (*Triticum sphaerococcum* Perc. and *T. persicum* Vav.) in Organic Farming: Influence of Sowing Density on Agronomic Traits, Pests and Diseases Occurrence, and Weed Infestation

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Abstract: Crop management should be determined to reintroduce ancient wheat. This study aimed to determine: i. the response of the yield of ancient wheat on sowing density; ii. the impact of sowing density on plant health, weed infestation and pest occurrence. Field experiments were carried out in Poland, on three organic farms. The factors were: (1) wheat species: Persian wheat (*Triticum persicum* Vav.) and Indian dwarf wheat (*T. sphaerococcum* Perc.), (2) sowing density (400, 500, and 600 grains m^{-2}). Increasing the sowing density of *T. sphaerococcum* from 400 to 600 grains m^{-2} increases the grain yield and reduces the pest pressure (*Oulema* spp. and Aphididae). Sowing densities did not affect the severity of powdery mildew at stem elongation as well as root rot and eyespot at the development of fruit. At the highest sowing density, the leaf area with tan spot symptoms was the highest. The eyespot symptoms occurred more frequently and the damaged plant surface caused by *Oulema* spp. was larger on *T. sphaerococcum*. Persian wheat turned out to be more susceptible to weed infestation. Indian dwarf wheat and Persian wheat are useful for organic farming, and the sowing density should be 500 or 600 grains m^{-2} and 400 grains m^{-2}, respectively.

Keywords: crop density; insects; organic cereals; sowing rate; tillering

1. Introduction

The total organic area in the EU-28 was 13.4 million hectares in 2018. From 2012 to 2018, the share of a total organic area in the total utilized agricultural area within the EU rose from 5.6% to 7.5%. It is still expected to grow in the coming years. Organic arable land exceeded 6 million ha, which represented 45.2% of the EU-28 total organic agricultural area in 2018 [1]. The world's largest organic farming areas are in Australia (43%) and Europe (24%) [2]. The value of the organic product market is the largest in Europe and North America. Organic farming offers an alternative to farms that cannot withstand growing competition on the conventional product market [2].

In recent years, EU policy has been focused on supporting agri-environmental programs, including organic production [3]. The reason for this is the intensification of agriculture in the 1980s, which caused a loss of biodiversity, increased soil erosion or nitrate emissions in rural areas, and deteriorated the health value of conventional foods. Support for organic farming is an example of policy reorientation towards its ecologization, and a factor enhancing sustainable development. It contributes to environmental protection as well as to the improvement of the social and economic situation in rural areas. The support of organic farming is one of the most important programs for rural development, being the instrument of II pillar of European Union Common Agriculture Policy (CAP) [3].

The growing interest in organic products has led to the rediscovery of ancient wheat as a valuable consumer raw material [4,5]. Growing of ancient wheat gives a chance to obtain consumable grain with a potentially higher content of biologically active components than in common wheat [2,6]. Partial recognition of ancient cereals, such as emmer wheat, einkorn wheat or spelt wheat, indicates their pro-health value in the context of diseases such as elevated cholesterol, colitis and allergies [4]. Increased content of Zn, Fe and Cu in grain was also found in these species compared to common wheat [7]. The usefulness of other ancient wheat species for economic use is not yet recognized. An example of such wheat is Indian dwarf wheat (*Triticum aestivum* L. ssp. *sphaerococcum* (Perc.) Mac Key, the synonym: *T. sphaerococcum* Perc. This species is endemic to southern Pakistan and northwestern India. It was one of the main crops grown by ancient Indian cultures. However, it disappeared from the record during the early twentieth century, especially after the Green Revolution brought modern wheat varieties into India and Pakistan [8]. *Triticum sphaerococcum* is a hexaploid species and has naked grains that can be completely thrashed from hulls [9]. The grain of *T. sphaerococcum* is hemispherical, with a shallow groove and has a high protein content [10]. Another, little known ancient wheat species is *Triticum persicum* Vav. (=*T. carthlicum* Nevski) with the common name of Persian wheat. It is early-maturing wheat with a spring growth habit. *Triticum persicum* belongs to the group of tetraploid kinds of wheat. This species comes from the southern slopes of the Greater Caucasus in Georgia [11]. Some sources indicate that this wheat was the result of the hybridization of domesticated emmer wheat and common wheat [9]. Crops of this plant can still be found in some countries, mainly in the South Caucasus, because it is resistant to stress factors of the habitat [12,13].

Development of methods for growing ancient wheat species may create variable conditions for their reintroduction on organic farms. One of the most important elements of cultivation technology in this farming system is the sowing density, which has a significant impact on weed infestation, the occurrence of diseases, pests, and the availability of minerals or water [14–17]. Sowing density in organic systems should balance a crop's competitive ability while maintaining grain yield and quality. The relationship between plant density and yield is not directly proportional due to the plasticity of the wheat plant. Plasticity refers to the compensatory ability of the crop to sustain yield by changing yield components. The use of higher sowing density can be a viable means of improving yield in organic spring wheat production, but differences in management, environment and weed pressures between farms will affect the outcome [18].

Plant stand design is a key parameter for the outcome of weed suppression [19,20]. Old cereal types, such as landraces, are commonly taller than modern varieties, which makes them more competitive against weeds [21]. The scientific literature lacks study results concerning the effect of sowing density on weed infestation of Indian dwarf wheat and Persian wheat. Research on common wheat is ambiguous. Auskalniene et al. [22] found no significant effect of increasing the sowing density of common wheat from 200 to 800 grains per m^2 on the number of weeds measured after plant emergence. In the study by Haliniarz and Kapeluszny [23], increasing the sowing density of common wheat from 500 to 800 grains per m^2 favored a significant reduction in both the number and weight of weeds before crop harvesting.

In organically grown cereal crops, pests appear that can pose a threat to the plants. Among them are *Oulema* spp. larvae and adults and Aphididae, especially in the years when meteorological conditions are favorable for their development. Ways to reduce the number of these insects in cereal plants include agrotechnical methods such as choosing the right site, maintaining spatial isolation, proper crop rotation, soil cultivation, selection of varieties, and regulation of stand density [24,25].

Important threats in cereal crops, including organic ones, are fungal diseases, which can contribute to significant losses in grain yield [14]. Of these, powdery mildew (*Blumeria graminis*), Septoria leaf blotch (*Zymoseptoria tritici*, *Septoria glumarum*), tan spot (*Pyrenophora tritici-repentis*), brown rust (*Puccinia recondita*) are most commonly found on wheat leaves, and recently, also stripe rust (*Puccinia striiformis*). Diseases affecting ears, such as Fusarium head blight (*Fusarium* spp.) and Septoria glume blotch (*Septoria glumarum*), also pose a great threat. In properly cultivated wheat crops, especially spring forms, take-all diseases usually do not pose the greatest threat, however, during the growing season the symptoms of take-all (*Gaeumannomyces graminis*), Fusarium foot rot (*Fusarium* spp.) and eyespot (*Oculimacula acuformis*, *Oculimacula yallundae*) can be observed, and less often, of sharp eyespot (*Rhizoctonia cerealis*, *Rhizoctonia solani*) [26–28]. The occurrence of diseases on wheat depends largely on weather conditions. The most important role is played by rainfall, including not only the total precipitation but also the frequency, as well as humidity in the crop stand. The occurrence of take-all diseases mainly depend on crop rotation, especially on the previous crop, but rainfall frequency is also important. The severity of diseases in wheat crops also depends on various other factors, including fertilization, cultivation, selection of varieties, sowing date and plant density [29,30].

This study aimed to determine the suitability of Indian dwarf wheat and Persian wheat for organic cultivation and to determine the optimal sowing density of these species, as well as to assess the effect of sowing density on morphological characteristics and plant health, pest occurrence and weed infestation. According to the research hypothesis, it was assumed that the sowing density influences the morphological features of wheat directly and indirectly related to the grain yield, but the responses of morphologically different genotypes of ancient wheat (Indian dwarf wheat and Persian wheat) will be various. It was also assumed that sowing density and genetic features of wheat species will influence the pressure of factors limiting the yield, i.e., the severity of pests, disease and weed infestation. The following research questions were posed: 1. Is it possible to grow Indian dwarf wheat and Persian wheat under organic farming? 2. What is the optimal sowing density of these wheat species. 3. What is the pressure of diseases, pests and weeds and what is the impact of sowing density and genetic features of wheat species on it?

2. Materials and Methods

2.1. Site Description and Crop Management

Three field experiments were located in three regions of Poland: Kuyavian-Pomeranian voivodeship (53°62′ N; 17°88′ E), (Kiełpin), Pomeranian voivodeship (54°05′ N; 18°54′ E) (Trzcińsk), Greater Poland voivodeship (52°11′ N; 18°80′ E) (Grabina Wielka). The content of available minerals in the soil, the pH and content of C-org. are presented in Table 1. The content of $N\text{-}NO_3$ and Mg at the experimental sites was similar. The lowest content of $N\text{-}NH_4$ P_2O_5 and K_2O was found in the soil in Kiełpin. The weather conditions were developed based on the Institute of Meteorology and Water Management (IMiGW) data and data made available by the Research Centre for Cultivar Testing (COBORU) (Table 2). The warmest area for the study was around Grabina Wielka and colder sites were Kiełpin and Trzcińsk. The highest amount of precipitation during the growing season was in Trzcińsk (233 mm) and the lowest was in Grabina Wielka (169 mm).

Table 1. Results of soil analysis before establishing field experiments.

Location	$N\text{-}NO_3$	$N\text{-}NH_4$	pH	P	K	Mg	C-org.
	mg kg^{-1} of Soil		(KCl)	mg kg^{-1} of Soil			%
Kiełpin	6.26	2.65	5.6	36.2	111.2	6.4	1.71
Trzcińsk	6.83	10.9	4.9	84.1	137.0	5.6	3.99
Grabina Wielka	8.64	9.99	5.9	64.5	182.6	5.7	1.63

Table 2. Mean air temperature and precipitation in the growing season at experimental sites.

Location	2019					1981–2010				
	March	April	May	June	July	March	April	May	June	July
					Temperature °C					
Kiełpin	4.9	9.0	11.3	20.4	17.4	2.0	7.2	12.5	15.1	17.6
Trzcińsk	5.8	8.6	11.9	20.0	18.0	1.9	7.1	12.4	15.3	18.0
Grabina Wielka	6.1	10.1	12.5	22.1	19.2	3.2	8.6	13.9	16.5	18.9
					Precipitation mm					
Kiełpin	46.0	3.0	69.4	63.3	39.5	41.3	32.9	57.2	62.7	70.3
Trzcińsk	44.0	2.0	65.0	63.0	59.0	30.0	30.0	54.0	67.0	73.0
Grabina Wielka	35.4	14.6	44.7	23.7	50.7	32,8	31.1	52.9	57.6	77.2

Cereals were the previous crop for the studied spring wheat species. Immediately after harvesting the previous crop (at the beginning of August 2018), the catch crop of a pea, a semi-leafless cultivar "Tarchalska", was sown in the amount of 240 kg ha^{-1}. The fertilizer for organic farming (Bioilsa) was applied in the total dose of 12 N, 10 P_2O_5, 26 K_2O, 4 MgO, and 20 SO_3 kg ha^{-1}. Before winter, fall ploughing was carried out to a depth of 22–23 cm. In spring, before sowing, the soil was cultivated with a tillage unit.

Sowing of the wheat was performed at the end of March 2019, in a narrow row spacing (10.5–12.5 cm, depending on the seeder used in particular farms). The seeding rate for particular sowing densities are presented in Table 3. In determining the seeding rate, the current seed parameters (thousand grain weight and germination capacity) and theoretical crop establishment (the ratio of seedlings vs. seeds) were adopted. Weeding harrowing was carried out before wheat emergence and at the beginning of tillering. Persian wheat ripened 7–10 days earlier than Indian dwarf wheat, however, for organizational reasons, both species were harvested at the same time (depending on location, from the end of July to mid-August), using a Wintersteiger plot harvester.

Table 3. Thousand-grain weight, germination capacity, theoretical establishment (ratio of seedlings vs. seeds) and the calculated se rate of *Triticum sphaerococcum* and *T. persicum*.

Species	1000-Grain Weight (g)	Germination Capacity (%)	Theoretical Crop Establishment (%)	Sowing Density (no m^{-2})	Seeding Rate (kg ha^{-1})
T. sphaerococcum	31.3	94	90	400 500 600	148 185 222
T. persicum	30.2	84	90	400 500 600	160 200 240

2.2. Experimental Design

The experiment was established in a split-plot design, in four replications. The whole-plots consisted of ancient wheat species: Indian dwarf wheat (*Triticum sphaerococcum* Perc.) and Persian wheat (*T. persicum* Vav.) (254 m^2), and subplots consisted of three germinating grain densities: 400, 500, 600 no m^{-2} (21 m^2).

2.3. Wheat Cultivars

The cultivar "Trispa" of Indian dwarf wheat was used in the study [31] (Figure 1a). This cultivar develops long, rather stiff stems (65–80 cm). The aboveground part of the plant is covered with the wax coating (very strong on the flag leaf sheath, medium on the blade), which increases its resistance to drought. The ear is medium-compact, (5 cm). The spikelets are two- or three-flowered, and one- or two-grained. Short awns are visible on the ear. The grain of Indian dwarf wheat is rounded and red. For Persian wheat, the cultivar "Persa" was used [31] (Figure 1b). The stems of this cultivar are delicate, long (65–80 cm), and very susceptible to lodging. There is no wax coating on the leaf blades, which increases the sensitivity of this species to drought. The medium long ear (7–8 cm) has a pyramidal shape. It is brownish, loose, and awned (awn length approx. 5 cm). The spikelets are two- or three-flowered, and one- or two-grained. Persian wheat is a naked form. Persian wheat grain is elongated and red. The grain of Persian wheat, similar to that of Indian dwarf wheat, is characterized by a much higher (compared to other wheat species) content of phenolic acids and alkylresorcinols, with proven pro-health effects [32].

Figure 1. Indian dwarf wheat (*Triticum sphaerococcum* Perc.) (**a**) and Persian wheat (*T. persicum* Vav.) (**b**).

2.4. Sampling and Measurements

2.4.1. Agronomic Traits

The plant density after emergence was determined as the number of plants per 1 m^2, estimated two or three weeks after sowing. At the heading stage (BBCH 59) [33], the length of generative tillers was determined on subsequent plants collected from a row with a length corresponding to an area of 0.5 m^2 on each plot. On the same plants, the number of generative and vegetative tillers per plant was determined. At full maturity (BBCH 89) [33], the number of generative fertile tillers (with grains) and sterile generative tillers (with ears without grains) was determined on test plots of 1 m^2. At the same development stage, 50 ears were randomly collected from each plot, on which the length of the ear, the number of fertile spikelets (with grains) and sterile spikelets (without grains) per ear and the number of grains per ear were measured. After harvest, grain yield and straw mass from each plot was determined. The 1000-grain weight was determined based on samples taken after achieving a constant grain moisture content of 12%, based on 500 pcs, in four replications of each treatment. During harvest, the yield and moisture contents of grain and straw were determined. Then, it was converted into a constant humidity of 15%.

2.4.2. Pests Occurrence

The pressure assessment of major insect pests (*Oulema* spp. adults and larvae; Aphididae adults and larvae) was performed organoleptically. The number of pests was determined (no), as well as the damaged plant surface (%) [34–36]. Observations were made at two wheat development stages: at the flag leaf stage (BBCH 39) and flowering (BBCH 65) [33], on 25 randomly selected plants, in four replications of each treatment.

2.4.3. Plant Diseases Occurrence

Health assessment included the analysis of the occurrence of take-all diseases, leaf and ear diseases. The severity of all currently occurring diseases was determined. The intensity of symptoms of powdery mildew, tan spot, Septoria leaf blotch, brown rust and stripe rust was determined on the leaves. Observations were made at the stages of stem elongation [33] and development of fruit [33]. In the first period, the health of the lower leaves (L 3–4) was assessed, and in the other, the health of the flag leaf (L 1) was evaluated, which was expressed as the percentage of leaf area with symptoms of a given disease. In the other period, the ear health was also determined, expressed as the percentage of ear surface with symptoms of Septoria glume blotch. The assessment of the severity of take-all diseases was made at fruit development. The severity of symptoms of root infestation by a complex of pathogens (*Gaeumannomyces graminis*, *Fusarium* spp., *Rhizoctonia* spp.) and stem base infestation by fungi of the genera *Fusarium*, *Oculimacula* and *Rhizoctonia* were determined. One hundred generative tillers from each combination were assessed for health. In laboratory conditions, after separating the tillers and removing the leaf sheaths, the percentage of infected stem bases or plant (for the roots) and the degree of infection on a scale of 0–4 was evaluated [37]. The degrees of infection were converted into the disease index (DI) using the formula of Townsend and Heuberger (0–100%) [38].

2.4.4. Weed Infestation

Weed infestation assessment was carried out at the end of the fruit development stage—late milk (BBCH 77) [33]. The number, species composition and weed dry mass were determined on each plot. The assessment was carried out on an area of 1 m^2 selected randomly on each plot. The dry mass of weeds was determined on a laboratory scale after drying the samples in a laboratory dryer in 48 h at 70 °C [39,40].

2.4.5. Statistical Analyses

The basic statistical descriptors included mean values $\overline{x}$ and standard deviation (±SD). For the other statistical analyses, the values were log-transformed log (x + 1) [41,42]. Normality of the distribution was tested with Kolmogorov–Smirnov test, while equality of variance in different samples was tested with a Levene test. Multifactorial analysis of variance was used to find significant differences between the means and in the case of significant differences, Tukey posthoc test was employed [43]. Based on the same log-transformed data set, the analysis of the influence of sowing density on agronomic traits, pest and disease occurrence of wheat species (*Triticum sphaerococcum* and *T. persicum*) with canonical correspondence analysis (CCA) was performed. This analysis was used to determine the influence of sowing density on agronomic traits, pest and disease occurrence of wheat species) because the structure of the data has a unimodal character [44–47]. For testing the significance of canonical axes in canonical correspondence analysis, a Monte Carlo-permutation test was used [47,48]. The level of significance for all statistical tests was accepted at $\alpha = 0.05$. The statistical calculations mentioned above were carried out with MS Excel 2019 software (Microsoft, Redmond, WA, USA, 2019), STATISTICA 13.3 (Dell, Round Rock, TX, USA, 2019), CANOCO 4.5 (Microcomputer Power, Ithaca, NY, USA, Microsoft) and PAST 3.2 (Hammer Øyvind, Natural History Museum, University of Oslo, Norway, 2018) software.

3. Results

3.1. Agronomic Traits

Plant density after the emergence of Indian dwarf wheat and Persian wheat in all sowing densities was lower than assumed (Table 4). Persian wheat had a slightly higher plant density than Indian dwarf wheat in sowing density of 500, and especially 600 no m^{-2}. This species also developed significantly more tillers per $plant^{-1}$, both generative ($p = 0.002$) as well as vegetative ($p = 0.031$). The number of generative tillers per $plant^{-1}$ at the lowest sowing density was slightly higher in both wheat species.

The grain yield of Indian dwarf wheat was significantly higher ($p < 0,001$) than that of Persian wheat, while the straw yield of both species was similar (Table 5). Increasing the sowing density from 400 to 600 no m^{-2} resulted in a significant ($p = 0.006$) increase in the grain yield of Indian dwarf wheat. However, no significant effect of sowing density on the grain yield of Persian wheat or the straw yield of any of the compared wheat species was demonstrated.

During observations made on generative tillers before harvest, the complete absence of kernels was found in some ears (Table 5). These were the smallest ears on the shortest tillers. There were significantly more ($p = 0.013$) tillers with such ears (sterile generative tillers) in Persian wheat (5%) relative to those found in Indian dwarf wheat (3.3%). The number of fertile generative tillers, as well as total generative tillers, was similar in both compared wheat species. At the highest sowing density 600 no m^{-2}, the number of fertile generative tillers of Indian dwarf wheat was significantly larger ($p = 0.003$) than of Persian wheat.

The length of generative tillers of the studied wheat species was similar and averaged 87 cm (Table 5). There was no significant effect of sowing density on the generative tiller length of Indian dwarf wheat or Persian wheat.

Indian dwarf wheat had a significantly shorter ear ($p < 0.001$) than Persian wheat (Table 6). The sowing density did not significantly affect the ear length of any of the compared wheat species.

The studied ancient wheat species were characterized by a fairly high proportion of sterile spikelets (without kernels) in ears (Table 6). Such spikelets were found at the base and the top of the ears. The number of such spikelets was significantly larger ($p < 0.001$) in Indian dwarf wheat. The number of fertile spikelets per ear^{-1} (with kernels), as well as the total number of spikelets per ear^{-1}, was also larger in Indian dwarf wheat than in Persian wheat ($p < 0.001$ and $p < 0.001$, respectively). Indian dwarf wheat at a sowing density of 600 no m^{-2} produced significantly more fertile spikelets ($p < 0.001$) and less sterile spikelets ($p = 0.001$) than it did at a sowing density of 400 no m^{-2}. In Persian wheat, however, there was only a tendency to produce more fertile spikelets at the lowest sowing density of 400 no m^{-2}.

The number of grains per spike was significantly larger ($p < 0.001$) in Indian dwarf wheat than in Persian wheat. Moreover, Indian dwarf wheat was shown to have significantly more grains per ear ($p = 0.001$) at a sowing density of 600 no m^{-2} as compared with 400 no m^{-2}. The sowing density, in turn, did not affect the number of grains per ear^{-1} of Persian wheat.

The thousand-grain weights (TGWs) of Indian dwarf wheat and Persian wheat were similar. The variation of sowing density did not have a significant effect on the thousand-seed weight of the compared wheat species.

Table 4. Plant density and tillering of *Triticum sphaerococcum* and *Triticum persicum* at different sowing densities, mean from three field experiments.

Species	Sowing Density	Plant Density (no m^{-2})	Generative Tillers (no $plant^{-1}$)	Vegetative Tillers (no $plant^{-1}$)	Generative and Vegetative Tillers (no $plant^{-1}$)
T. sphaerococcum	400	355 ± 45	1.31 ± 0.12	0.77 ± 0.67	2.08 ± 0.43
	500	439 ± 53	1.17 ± 0.11	0.67 ± 0.27	1.84 ± 0.35
	600	490 ± 103	1.21 ± 0.11	0.55 ± 0.21	1.77 ± 0.25
T. persicum	400	342 ± 48	1.46 ± 0.28	0.71 ± 0.38	2.16 ± 0.61
	500	455 ± 68	1.30 ± 0.19	0.85 ± 0.34	2.14 ± 0.43
	600	536 ± 42	1.32 ± 0.20	0.87 ± 0.30	2.19 ± 0.40
p-value		0.271	0.913	0.068	0.275
T. sphaerococcum		428 ± 90	1.23 ± 0.13 b [1]	0.66 ± 0.31 b	1.90 ± 0.37 b
T. persicum		444 ± 96	1.36 ± 0.23 a	0.81 ± 0.34 a	2.17 ± 0.47 a
p-value		0.290	0.002	0.031	0.003

[1] Mean values ± standard deviation (SD) in column followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

Table 5. Grain and straw yield, generative tiller number and length of *Triticum sphaerococcum* and *Triticum persicum* at different sowing densities, mean from three field experiments.

Species	Sowing Density	Grain Yield (Mg ha^{-1})	Straw Yield (Mg ha^{-1})	Fertile Generative Tillers (no m^{-2})	Sterile Generative Tillers (no m^{-2})	Total Generative Tillers (no m^{-2})	Generative Tillers Length (cm)
T.sphaerococcum	400	2.70 ± 0.82 b [1]	5.29 ± 2.77	410 ± 65 ab	15.0 ± 12.7	425 ± 66 ab	90.2 ± 12.7
	500	2.83 ± 0.94 ab	4.75 ± 2.07	427 ± 97 ab	18.3 ± 10.2	446 ± 100 ab	86.8 ± 11.4
	600	2.97 ± 1.00 a	5.23 ± 2.20	488 ± 102 a	12.0 ± 8.5	500 ± 102 a	87.1 ± 11.4
T. persicum	400	2.25 ± 0.79 c	4.70 ± 1.95	453 ± 76 ab	22.3 ± 15.7	475 ± 73 ab	86.8 ± 5.8
	500	2.09 ± 0.80 c	5.16 ± 2.09	393 ± 70 b	22.0 ± 14.8	415 ± 69 ab	86.9 ± 6.6
	600	2.11 ± 0.76 c	4.96 ± 1.66	381 ± 42 b	19.1 ± 15.0	400 ± 53 b	85.7 ± 6.7
p-value		0.006	0.176	0.003	0.774	0.003	0.427
T. phaerococcum		2.83 ± 0.91 a	5.09 ± 2.31	442 ± 94	15.1 ± 10.6 b	457 ± 94	88.0 ± 11.6
T. persicum		2.15 ± 0.76 b	4.94 ± 1.86	409 ± 70	21.1 ± 14.8 a	430 ± 72	86.5 ± 6.2
p-value		<0.001	0.293	0.056	0.013	0.125	0.143

[1] Mean values ± standard deviation (SD) in column followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

Table 6. Ear characteristics and 1000-grain weight of *Triticum sphaerococcum* and *T. persicum* at different sowing densities, mean from three field experiments.

Species	Sowing Density	Ear Length (cm)	Fertile Spikelets (no ear^{-1})	Sterile Spikelets (no ear^{-1})	Spikelets-Total (no ear^{-1})	Number of Grain per ear	1000-Grain Weight (g)
T. sphaerococcum	400	5.93 ± 0.52	13.1 ± 0.7 bc [1]	5.8 ± 1.1 a	18.9 ± 1.4 a	25.1 ± 2.2 bc	27.8 ± 3.1
	500	6.13 ± 0.66	13.7 ± 1.2 ab	5.2 ± 0.7 ab	18.9 ± 1.6 a	27.3 ± 2.4 ab	28.3 ± 5.3
	600	6.33 ± 0.52	14.3 ± 1.1 a	4.9 ± 0.6 b	19.3 ± 1.0 a	29.4 ± 3.0 a	29.2 ± 4.8
T. persicum	400	7.87 ± 0.98	12.4 ± 1.3 cd	2.3 ± 0.4 c	14.6 ± 1.4 b	24.5 ± 4.3 c	27.6 ± 4.2
	500	8.02 ± 0.81	11.8 ± 1.4 d	2.7 ± 0.3 c	14.5 ± 1.4 b	22.7 ± 3.0 c	28.1 ± 3.7
	600	8.01 ± 0.54	11.8 ± 0.7 d	2.3 ± 0.6 c	14.1 ± 0.8 b	24.0 ± 3.6 c	27.6 ± 5.4
p-value		0.460	<0.001	0.001	0.012	0.001	0.266
T. sphaerococcum		6.13 ± 0.58 b	13.7 ± 1.1 a	5.3 ± 0.9 a	19.0 ± 1.5 a	27.2 ± 3.2 a	28.5 ± 4.4
T. persicum		7.97 ± 0.78 a	12.0 ± 1.2 b	2.4 ± 0.5 b	14.4 ± 1.2 b	23.7 ± 3.4 b	27.8 ± 4.4
p-value		<0.001	<0.001	<0.001	<0.001	<0.001	0.094

[1] Mean values ± standard deviation (SD) in column followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

3.2. Pests

The studied wheat species were inhabited by the most important cereal crop pests from the economic point of view (*Oulema* spp. and Aphididae) (Table 7). Their numbers at both assessment periods (at the flag leaf stage and flowering) were very low. Both in Indian dwarf wheat and Persian wheat, the numbers of *Oulema* spp. larvae were larger at the flag leaf stage than at the flowering stage. A difference was observed in the preferences of this pest larvae as to the wheat species. *Triticum sphaerococcum* was much more attractive food for *Oulema* spp. larvae than *T. persicum*, which is well illustrated by canonical correspondence analysis (Figure 2).

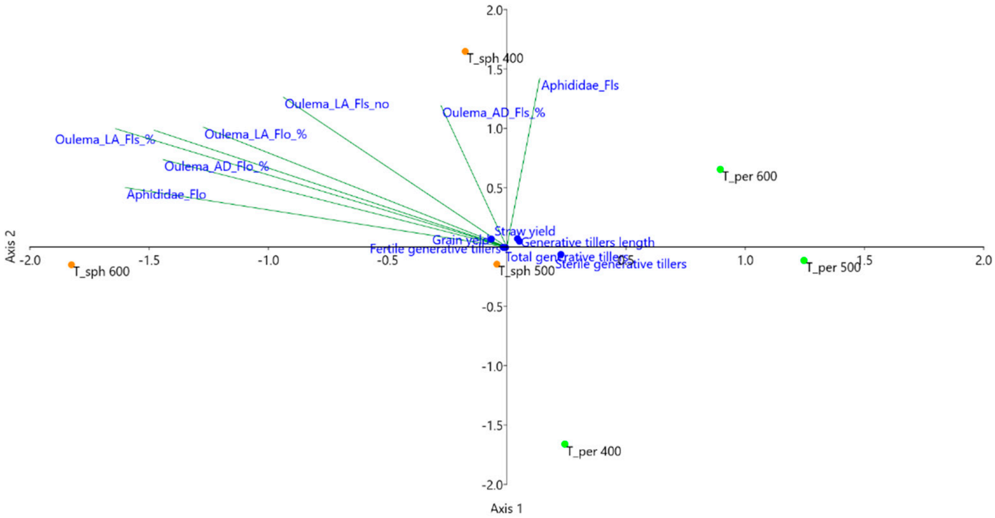

Figure 2. Canonical correspondence analysis (CCA) for grain and straw yield, generative tiller number and length, the number of pests and damaged plant surface of *Triticum sphaerococcum* (T_sph.) and *T. persicum* (T_per) at different sowing densities; eigenvalues for axis 1λ = 0.01 (79.63%), for axis 2λ = 0.01 (19.45%), significance of first axis: Monte Carlo-permutation test: (F-ratio = 0.1, p = 0.564), significance of second axis: Monte Carlo-permutation test: (F-ratio = 0.1, p = 0.841); LA—larvae, AD—adults, Fls—flag leaf stage, Flo—flowering.

In Aphididae, the opposite situation was observed compared to the larvae of *Oulema* spp. A larger number of aphids (including mainly *Sitobion avenae*) occurred at the flowering stage than at the flag leaf stage. As with *Oulema* spp. larvae, Indian dwarf wheat proved to be a more attractive food for aphids than Persian wheat (Table 7, Figure 2). The plant surface damaged by *Oulema* spp. adults and larvae was usually larger at the flowering stage than at the flag leaf stage. Analysis of the effect of spring wheat sowing density on the numbers of *Oulema* spp. and Aphididae and the signs of damage on plants arising after their attack showed that Indian dwarf wheat cultivated at the lowest sowing density (400 no m^{-2}) is the most preferred by the insects (Table 7, Figure 2).

Table 7. The number of pests and damaged plant surface of *Triticum sphaerococcum* and *Triticum persicum* at different sowing densities, mean from three field experiments.

Species	Sowing Density	*Oulema* spp. Larvae	Aphididae	*Oulema* spp. Adults	*Oulema* spp. Larvae	*Oulema* spp. Larvae	Aphididae	*Oulema* spp. Adults	*Oulema* spp. Larvae
		(no per 25 Shoots)		Damaged Plant Surface (%)		(no per 25 Shoots)		Damaged Plant Surface (%)	
		Flag Leaf Stage (BBCH 39)				Flowering (BBCH 65)			
T. sphaerococcum	400	4.00 ± 3.28 a [1]	0.25 ± 0.45 a	2.83 ± 3.19 a	3.25 ± 2.73 a	0.17 ± 0.39	1.17 ± 1.19	5.08 ± 2.35	7.08 ± 6.26 a
	500	2.42 ± 1.98 b	0.00 ± 0.00 b	1.75 ± 1.71 b	2.00 ± 1.60 b	0.08 ± 0.29	1.00 ± 1.04	5.08 ± 2.19	5.58 ± 4.08 b
	600	1.67 ± 0.78 b	0.00 ± 0.00 b	1.08 ± 0.67 b	2.50 ± 0.90 b	0.17 ± 0.39	1.08 ± 1.16	4.50 ± 1.93	4.92 ± 1.88 b
T. persicum	400	0.33 ± 0.49 c	0.00 ± 0.00 b	1.33 ± 1.15 b	0.42 ± 0.67 c	0.0 ± 0.0	0.50 ± 0.67	1.25 ± 0.62	1.67 ± 1.67 c
	500	0.08 ± 0.29 c	0.08 ± 0.29 b	1.00 ± 0.85 b	0.0 ± 0.0 c	0.0 ± 0.0	0.08 ± 0.29	0.58 ± 0.67	1.08 ± 1.16 c
	600	0.33 ± 0.49 c	0.00 ± 0.00 b	1.08 ± 1.16 b	0.08 ± 0.29 c	0.0 ± 0.0	0.08 ± 0.29	0.58 ± 0.51	1.17 ± 0.83 c
p-value		<0.001	0.026	0.001	0.042	0.762	0.484	0.169	0.045
T. sphaerococcum		2.69 ± 2.40 a	0.08 ± 0.28	1.89 ± 2.19 a	2.58 ± 1.92 a	0.14 ± 0.35 a	1.08 ±1.11 a	4.89 ± 2.12 a	5.86 ± 4.42 a
T. persicum		0.25 ± 0.44 b	0.03 ± 0.17	1.14 ± 1.05 b	0.17 ± 0.45 b	0.00 ± 0.00 b	0.22 ± 0.48 b	0.81 ± 0.67 b	1.31 ± 1.26 b
p-value		<0.001	0.310	<0.001	<0.001	0.020	<0.001	<0.001	<0.001

[1] Mean values ± standard deviation (SD) in column followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

3.3. Diseases

During the first disease severity assessment (at the stem elongation stage), the symptoms of powdery mildew and tan spot were found on wheat leaves. The severity of powdery mildew on *T. sphaerococcum* and *T. persicum* was similar and did not depend on sowing density. Significantly more ($p < 0.001$) tan spot symptoms were found on Persian wheat, especially grown in the highest sowing density (600 no m^{-2}) (Table 8, Figure 3a). On the other hand, sowing density did not differentiate the intensity of brown rust, stripe rust, Septoria leaf blotch and Septoria glume blotch. However, CCA analysis showed a stronger relationship of these diseases with the highest sowing density (Figure 3a). During the second disease severity assessment (at the fruit development stage), the most symptoms of the tan spot were found, while fewer symptoms of brown rust, and then of powdery mildew and Septoria leaf blotch were identified (Table 8). At that time of assessment, leaf and ear disease symptoms were more common on Indian dwarf wheat (Figure 3a). The leaves of this species had significantly more symptoms of brown rust ($p < 0.001$) and powdery mildew ($p < 0.001$) (Table 8). The symptoms of stripe rust and Septoria glume blotch were found only on Indian dwarf wheat. The sowing density significantly affected only the intensity of symptoms of a tan spot ($p = 0.012$) and powdery mildew ($p = 0.028$). Significantly more ($p = 0.012$) symptoms of the tan spot were observed on Indian dwarf wheat plants at a sowing density of 600 no m^{-2}, relative to those found at 400 and 500 no m^{-2}. Canonical correspondence analysis indicates the strongest relationship of agronomic traits with the occurrence of brown rust (correlation with Axis 1 = 0.78) (Figure 3a). The development of agronomic traits was also strongly associated with the occurrence of Septoria glume blotch and powdery mildew in Indian dwarf wheat, and with occurrence of tan spot in Persian wheat (the length of disease vectors is proportional to the rate of agronomic traits changes) (Figure 3a).

Of the take-all diseases, eyespot and root rot were the most severe (Table 9). Significantly more symptoms of eyespot ($p < 0.001$), Fusarium foot rot ($p = 0.008$) and sharp eyespot ($p = 0.018$) were observed on the plants of Indian dwarf wheat, while the intensity of root rot was slightly higher on Persian wheat (Table 9, Figure 3b). Genetic variability of agronomic traits had the strongest relationship with the occurrence of eyespot and sharp eyespot (correlation with Axis 1 = 0.87 and 0.80, respectively) (Figure 3b). No significant effect of sowing density of Indian dwarf wheat and Persian wheat on the percentage of plants with symptoms of individual take-all diseases was found, as well as for infestation expressed using the disease index (Table 9). However, canonical correspondence analysis (Figure 3b) indicates a stronger relationship between the occurrence of diseases such as Fusarium foot rot, eyespot and sharp eyespot and Indian dwarf wheat at the highest sowing density of 600 no m^{-2}.

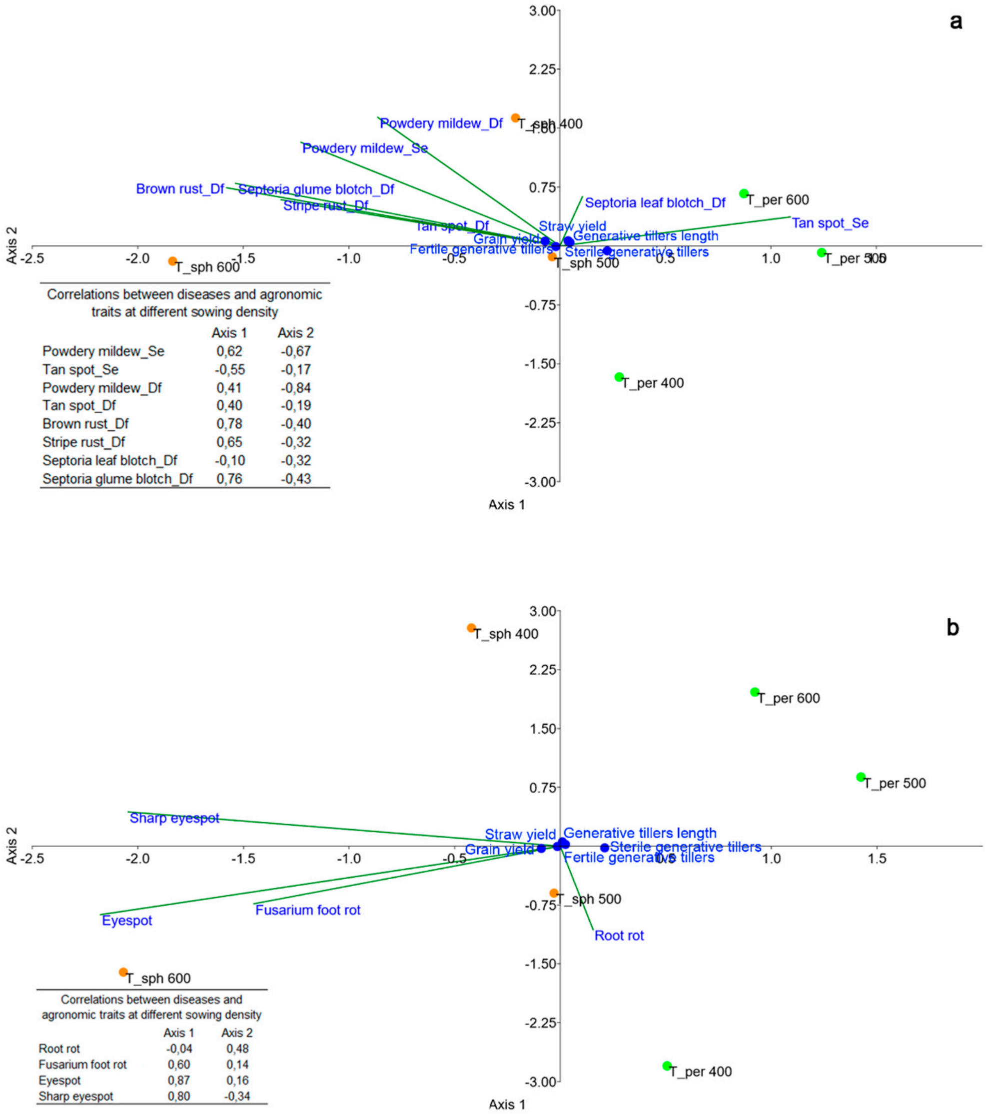

Figure 3. Canonical correspondence analysis for grain and straw yield, generative tiller number, length and (**a**) leaf and ear diseases of *T. sphaerococcum* (T_sph) and *T. persicum* (T_per) eigen values for axis 1λ = 0.01 (80.52%), for axis 2λ = 0.01 (18.54%), significance of first axis: Monte Carlo-permutation test: (F-ratio = 0.1, p = 0.422), significance of second axis: Monte Carlo-permutation test: (F-ratio = 0.1, p = 0.831), (**b**) foot and root rot diseases at development of fruit of *Triticum sphaerococcum* and *Triticum persicum*, eigen values for axis 1λ = 0.01 (92.53%), for axis 2λ = 0.01 (7.28%), significance of first axis: Monte Carlo-permutation test: (F-ratio = 0.1, p = 0.548), significance of second axis: Monte Carlo-permutation test: (F-ratio = 0.1, p = 0.878); Se—stem elongation, Df—development of fruit.

Table 8. Leaf and ear diseases of *Triticum sphaerococcum* and *T. persicum* at different sowing densities, mean from three field experiments.

Species	Sowing Density	Powdery Mildew	Tan Spot	Powdery Mildew	Tan Spot	Brown Rust	Stripe Rust	Septoria Leaf Blotch	Septoria Glume Blotch
		Leaf or Ear Area with Disease Symptoms (%)							
		Stem Elongation (BBCH 35–37)		Development of Fruit (BBCH 75–77)					
T. sphaerococcum	400	26.8 ± 29.4	5.58 ± 3.84 b [1]	1.00 ± 1.30 a	7.67 ± 5.72 bc	4.53 ± 5.00	0.31 ± 0.52	0.33 ± 0.62	9.78 ± 7.68
	500	25.8 ± 28.2	4.33 ± 3.46 b	0.61 ± 0.97 ab	7.57 ± 5.42 bc	4.48 ± 3.93	0.47 ± 0.78	0.44 ± 0.81	9.67 ± 7.33
	600	27.9 ± 29.5	4.96 ± 3.32 b	0.63 ± 0.97 ab	10.11 ± 7.42 a	4.73 ± 4.33	0.33 ± 0.79	0.11 ± 0.17	9.92 ± 8.62
T. persicum	400	22.5 ± 21.2	6.31 ± 5.60 b	0.28 ± 0.54 b	6.90 ± 8.66 c	0.87 ± 0.74	0.0 ± 0.0	0.14 ± 0.26	0.0 ± 0.0
	500	23.4 ± 20.6	6.44 ± 4.86 b	0.40 ± 0.66 b	9.26 ± 12.32 ab	0.72 ± 0.54	0.0 ± 0.0	0.21 ± 0.41	0.0 ± 0.0
	600	26.8 ± 21.9	10.84 ± 9.34 a	0.47 ± 0.62 b	8.46 ± 11.02 abc	0.69 ± 0.54	0.0 ± 0.0	0.11 ± 0.19	0.0 ± 0.0
p-value		0.803	<0.001	0.028	0.012	0.910	0.669	0.369	0.915
T. sphaerococcum		26.8 ± 28.2	4.96 ± 3.48 b	0.75 ± 1.07 a	8.45 ± 6.18	4.58 ± 4.31 a	0.37 ± 0.69 a	0.30 ± 0.60	9.79 ± 7.67 a
T. persicum		24.3 ± 20.7	7.86 ± 7.02 a	0.38 ± 0.60 b	8.21 ± 10.51	0.76 ± 0.60 b	0.00 ± 0.00 b	0.15 ± 0.29	0.00 ± 0.00 b
p-value		0.195	<0.001	<0.001	0.598	<0.001	<0.001	0.054	<0.001

[1] Mean values ± standard deviation (SD) in column followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

Table 9. Foot and root rot diseases at development of fruit of *Triticum sphaerococcum* and *T. persicum* at different sowing densities, mean from three field experiments.

Species	Sowing Density	Root Rot		Fusarium Foot Rot		Eyespot		Sharp Eyespot	
		DI	%	DI	%	DI	%	DI	%
T. sphaerococcum	400	7.00 ± 4.00	28.0 ± 16.0	1.17 ± 0.94	4.67 ± 3.75	9.7 ± 3.45	38.0 ± 14.2	0.17 ± 0.39	0.67 ± 1.56
	500	8.25 ± 3.93	32.7 ± 15.9	2.33 ± 1.78	9.33 ± 7.10	10.3 ± 5.93	40.7 ± 22.6	0.00 ± 0.00	0.00 ± 0.00
	600	7.75 ± 3.96	31.0 ± 15.8	2.08 ± 2.50	8.33 ± 10.01	10.9 ± 6.68	42.7 ± 25.3	0.17 ± 0.39	0.67 ± 1.56
T. persicum	400	8.75 ± 4.18	35.0 ± 16.7	0.75 ± 1.29	3.00 ± 5.15	8.2 ± 4.61	32.7 ± 18.4	0.0 ± 0.0	0.0 ± 0.0
	500	6.83 ± 3.95	27.0 ± 15.3	1.33 ± 2.53	5.33 ± 10.14	5.5 ± 4.32	22.0 ± 17.3	0.0 ± 0.0	0.0 ± 0.0
	600	8.83 ± 4.73	35.3 ± 18.9	0.50 ± 0.67	2.00 ± 2.70	6.1 ± 4.70	24.3 ± 18.8	0.0 ± 0.0	0.0 ± 0.0
p-value		0.283	0.278	0.431	0.431	0.235	0.235	0.232	0.232
T. sphaerococcum		7.67 ± 3.88	30.6 ± 15.6	1.86 ± 1.87 a [1]	7.44 ± 7.48 a	10.3 ± 5.39 a	40.4 ± 20.7 a	0.11 ± 0.32 a	0.44 ± 1.27 a
T. persicum		8.14 ± 4.28	32.4 ± 17.0	0.86 ± 1.68 b	3.44 ± 6.70 b	6.6 ± 4.56 b	26.3 ± 18.3 b	0.00 ± 0.00 b	0.00 ± 0.00 b
p-value		0.580	0.577	0.008	0.008	<0.001	<0.001	0.018	0.018

[1] Mean values ± standard deviation (SD) in column followed by different letters indicate significant differences between treatments at $p \leq 0.05$; DI—disease index; %—percentage of plants.

3.4. Weeds

The dry mass of weeds found in the Persian wheat stand was significantly higher (p = 0.013) than that found in Indian dwarf wheat (Table 10). No effect of sowing density on this trait has been demonstrated yet. However, there was a tendency to reduce the weed mass as the sowing density increased. It was particularly pronounced in the cultivation of Persian wheat. No interaction was found between the experimental factors regarding weed dry matter at the milk stage.

Table 10. Weed infestation of *Triticum sphaerococcum* and *T. persicum* at different sowing densities, mean from three field experiments.

Species	Sowing Density	Dry Matter of Weeds (g m^{-2})	Number of Weeds (no m^{-2})
T. sphaerococcum	400	61.1 ± 46.3	57.9 ± 44.4
	500	60.9 ± 46.2	49.0 ± 42.1
	600	57.4 ± 44.4	52.4 ± 41.9
T. persicum	400	91.9 ± 78.0	59.2 ± 43.1
	500	75.8 ± 68.4	51.0 ± 38.4
	600	62.4 ± 49.8	50.3 ± 38.2
p-value		0.280	0.865
T. sphaerococcum		59.8 ± 44.3 b [1]	53.1 ± 41.7
T. persicum		79.7 ± 65.7 a	53.5 ± 39.0
p-value		0.013	0.906

[1] Mean values ± standard deviation (SD) in column followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

The number of weeds per stand was not dependent on the sowing density or the wheat species. Wheat crops were dominated by dicotyledonous weeds, especially *Centaurea cyanus* L., *Chenopodium album* L., *Anthemis arvensis* L. and *Viola arvensis* Murr. Among monocotyledonous weeds, the most common were *Agropyron repens* L., *Apera spica-venti* L. and *Poa annua* L.

4. Discussion

Despite the theoretical crop establishment rate (planting vs. seedlings ratio) of 90% adopted to determine the seeding rate, no planned plant density after emergence was obtained in any treatment (Table 4). The actual mean establishment rate was less than the theoretical one and amounted to 80%. In the study by Beavers et al. [18] on spring common wheat in organic cultivation, the establishment rate was even lower and amounted to 55.5% and 76.3% in the next two years of research. The studies by Beavers et al. [18] and Tokatlidis [49] on common wheat indicate that the crop establishment rate decreases as the sowing density increases. According to Tokatlidis [49], the decrease is 4.8 p.p. for every 100 live seeds m^{-2}. In the present study, a similar relationship was observed only in Indian dwarf wheat between the seeding density of 500 and 600 no m^{-2}. Beavers et al. [18] report that crop establishment depends on not only sowing density but also on the environmental conditions, mostly on soil moisture and temperature.

Tillering of the studied ancient wheat species was poor. They developed on average 1.3 generative tillers and 0.74 vegetative tillers from one plant. Persian wheat developed significantly more generative and vegetative tillers per plant. The number of generative tillers per plant^{-1} in spring common wheat under organic farming is usually larger (1.36–2.02) [18]. In the present study, the number of generative tillers per plant of the studied wheat species was slightly larger at the lowest sowing density. Similar relationships are presented by Beavers at al. [18] for spring common wheat, for which the number of ears per plant^{-1} was significantly larger at a sowing density of 330 no m^{-2} compared to the number found at higher densities of 412 and 495, and the smallest at a density of 660 no m^{-2}.

Indian dwarf wheat gave yield at a good level (2.83 Mg ha^{-1}) (Table 5). The lower grain yield was obtained from Persian wheat (2.15 Mg ha^{-1}). In one of the organic farms where our experiments were carried out, the yield of common wheat grain obtained by a farmer in the production field was 100 kg ha^{-1} lower than that of Indian dwarf wheat. Poutala et al. [50] report that the mean yield of nine spring wheat cultivars in an organic cropping system was 2.17 Mg ha^{-1} and accounted for 51% of the yield in the conventional cropping system.

Persian wheat was characterized by a fast growth rate and slightly higher plant density after emergence than Indian dwarf wheat. However, the final number of fertile tillers per unit area determined before the harvest was similar in the compared wheat species. Only a significantly higher density of sterile generative tillers (without kernels) was found in Persian wheat. On average, in fertile spikelets of both ancient wheat species, there were two grains. However, Indian dwarf wheat was characterized by a larger number of such spikelets than Persian wheat. This increased the number of grains per ear and in the absence of differences in TGW of the compared species, it was the basic yield component decisive for increasing the grain yield of Indian dwarf wheat. The reason for the lower yield of Persian wheat, in addition to morphological traits, could also be a faster growth rate (by 7–10 days) compared to Indian dwarf wheat, which substantially shortened the period of yield accumulation.

In Indian dwarf wheat, the increase in sowing density from 400 to 600 no m^{-2} resulted in a significant increase in grain yield. This was due to the increase in the number of fertile spikelets, and consequently, the number of grains per ear (Table 6). Moreover, a tendency to increase the density of fertile generative tillers in a sowing density of 600 no m^{-2} was observed, but there was no significant effect of sowing density on the weight of the thousand-seed weight of this species. On the contrary, Poutala et al. [50] indicate a decrease in spring common wheat TGW with an increase in sowing density, but they compared the sowing density 600 and 900 no m^{-2}. In the study by Beavers et al. [18], the grain yield of spring common wheat in an organic cropping system increased at a sowing density of 660 no m^{-2} compared to densities of 330, 412 and 495 no m^{-2}, due to an increase in ears per m^{-2}, but there were no differences for ears per $plant^{-1}$ or TGW and few differences among densities for grain per ear^{-1}.

There was no significant effect of sowing density on Persian wheat grain yield, although a slightly higher grain yield was obtained at the lowest sowing density. Similarly, Poutala et al. [50] showed no effect of sowing density on the grain yield of spring common wheat. Lloveras et al. [51] claimed that wheat can compensate for low populations by modifying the number of tillers, as well as the number of grains per ear and area. In our study, Persian wheat only showed a tendency to increase the density of fertile generative tillers and the number of fertile spikelets at the lowest sowing density of 400 no m^{-2}, but no differences in the number of grains per ear or TGW were observed for different sowing densities.

The straw yields of Indian dwarf wheat and Persian wheat were similar. This was due to the lack of differences in the density and length of tillers of the compared species. In addition, no significant effect of the sowing density on straw yield or tiller length of any species was found. The study on common wheat in conventional cultivation has shown a significant effect of the sowing density on the length of shoots [52], while the tillers of the studied wheat cultivars in this study were on average eight cm higher than in our experiment.

In the present study, it was found that both wheat species were infrequently inhabited by pests, including mainly *Oulema* spp. and Aphididae (Table 7) (many times lower than the reported threshold of economic harmfulness for these species feeding on spring wheat). Similar threats are pointed out by Gałęzewski [53]. According to his research, the mean number of *Oulema* spp. larvae on spring wheat was 3.85 no per 30 tillers, while for aphids it was 9.83 no per 30 tillers, which does not exceed the threshold of economic harmfulness. The numbers of *Oulema* spp. larvae were larger at the flag leaf stage than at the flowering stage, which is a natural phenomenon because the larvae pass into the next developmental stage (pupation occurs). The time of appearance of individual developmental stages of *Oulema* spp. and Aphididae in the present study is consistent with the data presented by other authors. Kaniuczak and Bereś [24] report that the peak in the presence of cereal leaf beetle imagoes on organic farms was from the 21st to 31st of May, while the peal presence of larvae occurred from the 1st to 10th of June. The peak of cereal aphids occurrence was between the 21st and 31st of May, but here the dominant species was the bird-cherry aphid. In the present study, the level of damage caused by feeding of *Oulema* spp. and Aphididae was low. In the study by Kaniuczak and Bereś [24], it was noted that exactly every 4th flag leaf is damaged by larvae of cereal leaf beetles, and the average percentage of damaged area (for the flag leaf) was as much as 20%. The plant surface damaged by *Oulema* spp. was usually larger at the flowering than at the flag leaf stage (Table 7). This is a completely normal situation because harmful stages of *Oulema* spp. still feed for a few to several days on plants, thus increasing the damaged surface of the plants.

In our study, Indian dwarf wheat grown at the lowest sowing density (400 no m^{-2}) was most preferred by insects. Earlier studies have shown that a smaller number of plants per unit area promotes better air circulation, which leads to a decrease in humidity inside the stand [54,55]. Such conditions appear to be more favorable to the occurrence of many plant pests.

Symptoms of diseases similar to those observed on common wheat were found on the analyzed Indian dwarf wheat and Persian wheat plants, both in conventional crops [26,56] and in organic crops [14,15]. More symptoms of powdery mildew, brown rust, stripe rust and Septoria glume blotch were found on Indian dwarf wheat plants. Consistently with the reports by Baccar et al. [29], the varied severity of diseases observed in the present study on the two studied wheat species may result from different stand structures. Tall plants are usually less attacked by leaf and ear pathogens Baccar [29]. Moreover, the leaf spatial distribution, their number, as well as their shape and size, have an impact. In the case of pathogens whose spores are spread by raindrops splashing from the lower infected leaves to the upper ones, the closer the leaves are to each other, the more easily the spores are transported up the plant [57]. In the present study, sowing density differentiated the intensity of powdery mildew and tan spot symptoms. At the fruit development stage, increased intensity of powdery mildew was observed on Indian dwarf wheat at the lowest sowing density (400 no m^{-2}). This is in line with the observations of Finckh et al. [58] who stated that in the case of susceptible wheat genotypes, the severity of powdery mildew symptoms increased along with a decrease in sowing density. This effect was not observed for resistant wheat genotypes. Part of the research conducted on winter wheat indicates that an increase in plant density contributes to the increased occurrence of this disease symptom [56,59]. The leaf area with tan spot symptoms was usually larger at a higher sowing density. However, the sowing density did not differentiate the intensity of the remaining diseases observed on leaves and ears. Additionally, no differentiation in the intensity of brown rust, stripe rust and Septoria glume blotch is observed on common wheat depending on the sowing density [56]. However, other studies indicate an increase in the symptoms of Septoria leaf blotch [59–61]. Dense sowing makes the plants closer together, which greatly facilitates the spread of pathogen spores. Moreover, sowing density can also indirectly affect the severity of diseases, inter alia, by changing the microclimate in the stand. In dense crops, the temperature is more uniform, the air humidity is higher, and water stays on the leaves longer, which promotes infection by fungi [29,62]. The distance between infected and healthy tissues is important. The closer the leaves are to each other, the easier it is to splash the fungal spores and thus control the plants by pathogens [57].

In the present study, no significant effect of sowing density on the occurrence of take-all diseases was noted. In addition, Eken et al. [63] found no effect of sowing density on the occurrence of root and crown rot diseases. On the other hand, other authors noted an increase in the severity of root and stem base diseases in winter wheat crops at higher sowing densities [28,64], which was particularly evident at the early developmental stages of the analyzed plants. In the case of take-all diseases, increased plant density means a shorter distance between the inoculum and host, which significantly increases the likelihood of the pathogen reaching, through developing mycelium or spores, the next plant and infecting it. Lemańczyk [28] in a stationary experiment also observed an increase in plant infection by fungi of the genus *Rhizoctonia* in the first year of wheat cultivation at higher plant density. However, in the following years, the annual cultivation of wheat in the same place contributed to the accumulation of inoculum in the soil and in the following years of cultivation the sowing density did not differentiate the severity of sharp eyespot symptoms.

In the present study, weed infestation of wheat was at an average level, typical of organic farming (Table 10). The studied wheat species did not show greater susceptibility to weed infestation than is observed in the spring common wheat grown under comparable conditions. In the study by Bhaskar et al. [65], weed mass in spring wheat grown without the use of herbicides was 52% lower, while in the study by Feledyn-Szewczyk [66], the number of weeds in spring wheat was about 70% larger than that found in Persian and Indian dwarf wheat. The present study did not confirm the effect of sowing density on weed infestation of wheat found by Haliniarz and Kapeluszny [23]. However, in one of three locations, an increase in sowing density from 400 to 500 grains per m^2 contributed to a reduction in weed numbers. No effect of sowing density on weed mass was found in any place. The studied species differed in this respect. A smaller mass of weeds found in Indian dwarf wheat compared to that found in Persian wheat could be due to its production of more generative tillers than the Persian wheat. This may indicate greater competitiveness of Indian dwarf wheat, which was also visible at a higher grain yield compared to Persian wheat.

5. Conclusions

Indian dwarf wheat and Persian wheat are useful for organic farming. For the maximum grain yield, Indian dwarf wheat should be sown at a density of 600 no m^{-2} and Persian wheat at 400 no m^{-2}. To determine the seeding rate, in addition to seed parameters (germination capacity, purity and TGW), a crop establishment of 80% should be taken into account. Of the pathogens infecting Indian dwarf wheat and Persian wheat, the greatest pressure can be expected from the fungi causing eyespot, root rot, powdery mildew, and to a lesser extent, tan spot. Eye spot symptoms are more severe on Indian dwarf wheat. Leaf surface with tan spot symptoms is usually larger at a higher sowing density. Pest pressure in the organic cultivation of Indian dwarf wheat and Persian wheat is low. *Oulema* spp. and Aphididae are the most common pests on Indian dwarf and Persian wheat. These pests prefer Indian dwarf wheat plants with the lowest sowing density. Persian wheat turned out to be more susceptible to weed infestation among the studied ancient wheat species.

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