

Article

Return of Ancient Wheats, Emmer and Einkorn, a Pesticide-Free Alternative for a More Sustainable Agriculture—A Summary of a Comprehensive Analysis from Central Europe

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Abstract

Conventional agriculture, focusing on productivity rather than sustainability, have long abandoned hulled wheats. With them not only striking genetic diversity but valuable, health-promoting food sources became lost. Although einkorn and emmer—two of the most ancient wheat species—are generally considered good candidates of sustainable agriculture especially for pesticide-free cropping, they have remained largely unrecognized. To assess their agronomic potential in comparison with modern wheats grown under the same conditions, comprehensive research was conducted, combining multi-location participatory on-farm and small-plot trials. Our findings confirmed that most landraces of emmer and einkorn exhibited strong weed suppression ability, making them suitable for organic cultivation, and effective resistance against diseases—including *Fusarium* spp. and associated deoxynivalenol (DON) mycotoxin accumulation. Both species were entirely avoided by cereal leaf beetles (*Oulema* spp.) and had, on average, 2.6% more grain protein content than common wheat. Although they command significantly higher market prices, their (hulled) yields were comparable to modern wheat only in extreme years or at sites typically producing 3–5 t/ha of wheat. Nevertheless, the cultivation of emmer and einkorn presents a more sustainable "sow-and-harvest" alternative, free from pesticide and mycotoxin residue risks, while also enhances biodiversity from the field to the table.

Keywords: ancient wheat; disease resistance; grain quality; organic farming; participatory research; pesticide-free cropping; sustainable agriculture; yield



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1. Introduction

1.1. Modern Agriculture and Ancient Wheats

High-input farming focuses on maximizing productivity, but often at the expense of a low relative return rate [1], and it relies heavily on the use of artificial fertilizers and biocides, which is in complete contrast to the principles of sustainable agriculture. In organic cultivation, where synthetic plant protection products are not allowed, the emphasis must be laid on biological bases, i.e., crop resistance to pests and weeds, and on nourishing the soil itself instead of the plants directly. In many aspects, sustainable and

organic farming share common goals, emphasizing soil health, biodiversity, and long-term resilience of agroecosystems. Organic farmers, however, often produce under limiting nutrient supply levels or even marginal conditions, especially in Hungary [2]. Low-input conditions do not support certain diseases, e.g., powdery mildew, *Septoria*, and rusts, and they are also restraining for weeds, such environments require crop varieties or even species that can stably achieve a good quality of yield [3,4].

Wild ancient wheats, einkorn, and emmer have co-existed for millions of years. Their consumption and later domestication by humankind induced major changes favourable for cultivation but contrasting with the natural spread habit of their wild ancestors [5]. Domestic einkorn—the so-called “single-grained” diploid wheat (*Triticum monococcum* L. subsp. *monococcum*)—and domestic emmer—“two-grained” tetraploid wheat (*Triticum turgidum* subsp. *dicoccum* Schrank)—were among the first widely cultivated plant species. Being extremely tall and having hulled grains, they have been gradually replaced by short, naked-grained—hulless—higher-performing species, such as the tetraploid durum wheat (*Triticum turgidum* subsp. *durum* Desf.) and the hexaploid bread wheat (*Triticum aestivum* L.), which became the dominant cultivated forms. Ancient wheats have only survived in marginal, remote areas and in a few small regions where traditions have kept them alive since the Bronze Age [6]. With their disappearance, not only was a valuable source of genetic diversity lost, but also cereals with exceptional nutritional qualities [7]. As they are generally considered to have good weed-suppression ability and disease resistance, ancient wheats could serve as promising candidates for organic and pesticide-free farming systems. Despite all potential benefits, in 2021 in Hungary, emmer was only cultivated on 44 ha, while einkorn was sown on 693 ha, compared to the most popular species among organic farmers, spelt (*Triticum spelta* L.), a hulled hexaploid wheat, which covered 16,400 ha [2].

1.2. Yield Perspectives and Grain Quality Attributes of Emmer and Einkorn

It is a matter of fact that under intensive cropping, the yields of emmer and einkorn are significantly lower than those of common wheat, but their yield stability is undeniably better under harsh climatic and poorer soil conditions [8]. From the two species, emmer exhibited greater yield stability, but einkorn often had a higher yield maximum [9–13]. As reported, maximum yield values ranged up to 3.5–4 t/ha in emmer and 5 t/ha in einkorn. However, a slight N-fertilization markedly increased the grain yield of emmer and einkorn [1].

Although the site and year have a great impact on yield quality, emmer and einkorn generally had markedly higher grain protein content, usually between 11 and 20%, compared to commercial wheat, ranging between 9 and 13% [1,13–19]. Protein digestibility was also reported to usually be better in the ancient wheat species than in common wheat [20,21], but it was found to be similar by Abdel-Aal and Hucl [14].

It is well-known that emmer and einkorn have markedly poorer bread-making quality than spelt and *aestivum* wheats [22,23], but they can be used for artisan bread products, pasta, and other dietary foodstuffs, like mueslies or flakes [15,18]. Their unique grain composition involves higher antioxidant capacity and bioactive compound levels (phenolics and carotenoids, e.g., lutein, flavonoids, phytosterols, and vitamin E) compared to bread wheat [13,24–27], with an elevated macro- and micro-element content [14,24,28,29] and a more favourable lipid and starch profile from a physiological and nutritional point of view. All these features make them suitable elements of special diets for people suffering from various diseases, such as colitis, diabetes, and high blood cholesterol [30,31], and certain allergies—except for those related to wheat, although emmer and einkorn might provoke a reaction less often [32,33].

1.3. Pest and Disease Resistance and Weed Suppression

The cereal leaf beetle (*Oulema* spp.)—and especially *Oulema melanopus* (L.), being of Eurasian origin—is a severe and economically relevant pest of cereal crops across Europe and North America [34]. It primarily attacks wheat, barley, oats, and rye, and occasionally feeds on other grasses [35]. The larvae are responsible for most of the damage, feeding between the leaf veins and producing elongated translucent lesions that give fields a silvered or bleached appearance, significantly reducing the plant's photosynthetic capacity [35,36]. Grain yield reduction reported in Europe ranged from 3% to 8% in Poland, 17% to 95% in the Netherlands, and 70% in central Europe [37]. In North America, yield losses of 55% in spring wheat, 23% in winter wheat, and 38–75% in oat and barley have been documented due to cereal leaf beetle infestations, while in Canada, yield losses reached 30% [37]. As a result of the damage caused, a substantial decrease in the milling and baking qualities was reported, including 30% less protein content and a 10% lower Hagberg falling number [38].

The highest preference for hosts was found in wheat, barley, and oat; however, less preferably, the beetle attacks rye and timothy, and, with the lowest preference, fescue, grain sorghum, and corn, but it cannot survive on Sudan grass, green foxtail, and wild cane [37]. Nevertheless, no mention in the literature was found reporting pest incidence in ancient wheats like spelt, emmer, and einkorn. It remains unclear whether this is because of a greater resistance or just because of a lack of data being available due to the lower economic relevance of these species.

The higher level of bioactive compounds in the ancient wheats might play a pivotal role in their strong resistance against fungi and other pests [24,39–43]. In both emmer and einkorn, some accessions were identified as resistance sources against various fungal diseases, including powdery mildew, stem, yellow, and leaf rusts, tan spots, *Septoria* blotch, bunts, and *Fusarium* [44–46]. Some landraces were even found to have outstandingly high overall disease resistance; furthermore, einkorn was resistant to most diseases, including powdery mildew, leaf spot diseases, yellow, and leaf rusts [13,44,47]. The susceptibility of the two species to *Fusarium* head blight (FHB) was similarly low [13]. Artificial field inoculation with *F. culmorum* isolates confirmed that emmer and einkorn were more resistant compared to common wheat and spelt, but no significant differences in mycotoxin accumulation in the infected grains were found between the species [46].

Bioactive compounds might also contribute to weed-suppression ability as the total amount of polyphenolics and flavonoid compounds in the shoot was related to the suppression of *Raphanus sativus* growth [48]. Furthermore, polyphenolics, and especially syringic acid, were associated with the allelopathic effects of emmer and common wheat. The fact that—in certain circumstances—einkorn has even more favourable general weed and ragweed (*Ambrosia artemisiifolia*) control features than emmer [49], suggests that these ancient wheats both have a great potential in herbicide-free crop production systems.

1.4. Background and Aims of the Present Research

Considering the high-quality attributes of emmer and einkorn, the Hungarian Research Institute of Organic Agriculture (ÖMKi) commenced investigations in 2015 to determine whether the landraces of these two underutilized ancient crops could be introduced and successfully grown under low-input and organic conditions in Hungary. Previous research on genebank accessions and commercial varieties confirmed that winter emmer and einkorn landraces yielded 3 t/ha on average, and some of them even outperformed commercial varieties [13]. Moreover, the grain protein content (being between 15 and 20%) and the total phenolic content were high in both species. Einkorn seeds contained 277% higher

bound and 63% higher total flavonoids, 62% more lipids, and had 243% higher antioxidant activity (DPPH) than emmer [13].

These results encouraged united efforts in the present work to clarify the most important agronomic aspects in an extended participatory research project that combined real-life situations of on-farm sites and multi-cultivar replicated trial designs. The aims of the present work were to determine the following:

- What yield potential do einkorn and emmer have, and how variable is their performance under various locations and crop-year characteristics?
- How do emmer and einkorn yields relate to those of modern wheats, and how do cultivation type, environment, and crop year influence this?
- How is the grain protein content of emmer and einkorn related to the varying environmental factors and to that of modern wheats?
- Are emmer and einkorn suitable for pesticide-free cultivation in terms of disease, pest, and weed resistance under organic and/or low-input farming conditions, while also considering economic aspects?

2. Materials and Methods

2.1. Plant Material Studied

Based on previous results, an assortment of promising emmer and einkorn landraces and varieties was selected for the study, including new accessions received from the Slovak University of Agriculture (Nitra, Slovakia). The final variety set included 8 einkorns, 13 winter and 3 spring emmers, and 6 spelts, as shown in Table 1. However, not all landraces and varieties were tested at all sites, and the full set was only tested in the Szár location, because in the on-farm participatory research scheme, it was up to the farmers' choice as to which (and how many) varieties they grew at their farm. Corresponding to this, the modern wheat varieties used for yield and quality comparisons with ancient wheats were either those cultivated or tested by the farmer at the same location as the ancient wheats. These modern varieties, however, were adapted to (recommended or even bred for) organic farming conditions.

2.2. Experimental Sites and Cultivation Types

Beginning from the crop year of 2018/2019, the experiments were conducted at various locations in Hungary and the Upland of Slovakia, incorporating various management systems, such as those certified as organic, those not certified but producing chemical-free, and conventional management. While providing different aspects, these multi-location participatory trials combined traditional small-plot experimentation with real-life performance of ancient wheats, based on the close collaboration between farmers, researchers, and breeders in the ÖMKi Living Laboratory network (certified by the European network of living laboratories, ENoLL). The present work summarizes the most significant findings from the extensive amount of data collected between 2019 and 2022.

The on-farm trial network is a participatory research approach that targets the preferences and needs of the farmers and their respective value chains. A key feature of this participatory experimentation is that depending on the farmers' choices and possibilities, not all varieties are sown in every location and, also, the test sites may vary between years. At the start, sowing seeds (typically one bag of 20–30 kg of each variety) are provided for the farmers, who are requested to sow them in strips (usually in the width of their sowing machine), side by side, in a fairly homogenous part of their field (Figure 1). This kind of real-life experimentation reflects the specificity of the local conditions, agricultural practices, and the usual routines of the farmers, using the facilities and equipment they apply in their everyday work.

Table 1. Einkorn, emmer, and spelt varieties and landraces tested in the experiments.

Species	Name/Code of Accession	Common Name/Type—Country
Winter einkorn	Mv ALKOR	registered variety—HU
	Mv MENKET	registered variety—HU
	Mv ESZTENA	registered variety—HU
	GT 2139	unknown/landrace—CH
	EBNERS einkorn	registered variety—AT
	NÖDIK einkorn (RCAT 074129)	landrace from Morocco (COLL. SCHIEMANN)
	Tifi	registered variety—NL
	BÖZÖDI einkorn	landrace—RO and HU
Winter emmer	Mv HEGYES	registered variety—HU
	NÖDIK emmer (RCAT 004664)	Emmer roter/German landrace
	GT 143	Schwarzwerdender/landrace—CH
	GT 381	Schwarzer
	GT 831	Samtemmer/landrace—CH
	GT 1399	Blauemmer/landrace—CH
	GT 1400	Grauer/landrace—CH
	GT 1402	Schwarzbehaarter/landrace—CH
	GUARDIAREGIA	Weisser behaarter/landrace—CH
	AGNONE	registered variety—IT
	MOLISE-SEL-COLLI	registered variety—IT
	FARVENTO	registered variety—IT
	PN-4-41	registered variety—AT
Spring emmer	GT 1669	breeding line—SK
	HOLLAND spring emmer	Schwarzer Eschikon/landrace—CH
	GT 1971	variety candidate—NL
Spelt	RUBIOTA	Weisser/landrace—CH
	EBNERS-ROTKORN	registered variety—CZ
	OBERKULMER-ROTKORN	registered variety—AT
	ALTGOLD	registered variety—DE
	OSTRO	registered variety—CH
	FRANCKENKORN	registered variety—AT
		registered variety—DE

Landraces with a GT code originated from the collection of the community gene bank ProSpecieRara (Basel, Switzerland), while those with RCAT were obtained from the National Centre for Biodiversity and Gene Conservation (Tápiószéle, Hungary). Registered varieties, breeding lines, and variety candidates were kindly provided by the Agricultural Institute, HUN-REN ATK (Martonvásár, Hungary), the Louis Bolk Institute (Driebergen-Rijsenburg, the Netherlands), and the Research Institute of Plant Production (Piešťany, Slovakia).

The plot size ranged between 0.1 and 0.6 ha for each cultivar. In 2018/2019, six on-farm sites (with 1–8 landraces and varieties, mean: 2.7 cultivars per site) and one research station (managing a strip trial with 15 entries in Martonvásár) were involved in the testing. In the second crop year, 2019/2020, there were eight on-farm sites (testing 1–8, mean: 3.1 entries) and one research station (managing a small-plot trial with 15 accessions in Martonvásár) that participated. In 2020/2021, there were 13 on-farm sites (1–23 einkorn and emmer accessions, mean: 5.4). For yield comparisons, we only included those locations where both ancient wheats and winter wheats were tested. As 2022 was an extraordinarily arid year in most on-farm locations, causing severe damage in the trials, these sites were excluded from the analyses (with the exception of Szár, which was not substantially affected). Most significant experimental sites, from which detailed data are presented in this paper, are characterized as follows.



Figure 1. Examples of the two main trial designs. Above: the small-plot trial in Szár in May, 2022. Below: part of the on-farm trial site in Želiezovce in June 2021.

The **Martonvásár on-station trial** (Central Hungary), managed by the Agricultural Institute, HUN-REN Centre for Agricultural Research (ATK): The soil type is chernozem in this location. In 2018/2019, a meso-plot strip trial was carried out here under conventional management. The plot size was 1 m × 50 m in 4 replications for winter emmers and einkorns and 1 plot for each spring emmer (sown in winter). Although no chemical plant protection treatment was applied, a relatively low (70–70 kg/ha) mineral NPK supply was provided. In 2019/2020, a 3-replication small-plot experiment (plot size: 6 m²) was carried out under organic management (at the organic experimental field of ATK).

On-farm test sites: The northern location of **Pásztó** has a thin layer of low-fertility, clay loam soil. The organic farm is managed extensively, and the applied minimum tillage system implies a strong weed presence. **Füzesgyarmat** is located in the Great Hungarian Plain, East Hungary, and has a loam soil type. At this organic farm, reduced tillage is applied, and nutrients are limited. Although the water supply is slightly better than

average, the site is also more exposed to inland water. **Želiezovce** (Upland, Slovakia) can be seen as an ideal arable cropping location, as soil conditions (clay loam) have been greatly enhanced in the past 30 years, due to the soil- and water-preserving organic agricultural practices and the regular use of manure produced on the farm.

The small-plot organic trial at the ‘Csoroszllya farm’ in **Szár** (Central Hungary): This on-farm site, testing the highest number of cultivars, has sandy loam soil with high fertility. From seed sowing till harvest, the experimental field was managed by the research station of the Agricultural Institute HUN-REN ATK (Martonvásár), in a small-plot trial system (with a 6 m² net plot size, and 3 replications in a randomized block design, Figure 1). Due to technical reasons (e.g., sowing and harvesting settings), modern wheats and ancient wheats were sown in separate sub-trials, although in adjacent plots. Apart from the small plots’ management, the land was cultivated by the farm personnel, who applied necessary treatments (e.g., harrowing). The experimental area was rotated each year, and previous ploughing was applied. The pre-crop was soybean in 2020/2021 and potato in 2021/2022. In the first year, mechanical harrowing took place in early March, while this step was omitted in the second crop year due to the late emergence of the plants. The Szár site was regularly surveyed, recording various data, e.g., germination, winter survival, plant coverage, heading and maturation dates, diseases, weeds and pests, plant height, and lodging.

2.3. Disease, Pest, and Weed Surveys

During the on-farm field surveys, data on the incidence and severity of relevant diseases and pests were recorded for each variety at each site. As on-farm locations were far from each other, due to travelling constraints, field surveys were performed at around anthesis and before harvest during May–June on these sites. In the small-plot trials, however, the plants were regularly surveyed using either the Saari–Prescott scale [50], 0–9 (for powdery mildew and leaf blotch diseases), and/or, in the case of other leaf pathogens, as the percentage of plants infected (incidence) and the percentage of leaves on plants showing disease symptoms (severity). In the case of *Fusarium*, head blight, spike infection incidence, and infection severity (coverage of the infected spikes) were recorded as percentage values. The grain infection rate was calculated as the percentage of the seeds exhibiting symptoms of *Fusarium* infection in three subsamples of the harvested yield. The *Fusarium* mycotoxin deoxynivalenol (DON) content was determined according to the VICAM DON test protocol for HPLC (VICAM DonTest GN-MC9560-1 Rev.B). The threshold value for the detection of DON was 100 µg/kg. According to Commission Regulation (EC) No 1881/2006, the maximum level for DON contamination in (unprocessed) cereal grains is 1250 µg/kg.

During the field trials, there was a significant incidence of cereal leaf beetle (*Oulema melanopus*) infestation at the Szár location, for which a 0–10 scale was applied to record the severity of infestation (0 meaning absolutely no incidence, 1 = up to 5%, 2–9 equalling up to 10, 20, 30, 40, 50, 60, 70, and 80%, and 10 = up to 100% of damage coverage). Weed coverage was recorded in the small-plot trial for each plot at the end of the heading period, scored according to a 0–5 scale, meaning no coverage up to 5, 15, 25, 35, and 50% surface weed coverage, respectively.

2.4. Yield Determination

The small-plot trials were harvested with a combine harvester at full maturation. In the case of the on-farm experimental network, yield data were obtained either based on the plot yield reported by the farmer (when exact measurement was possible) or as yield estimation, made after full maturity, via collecting the spikes with a sickle from

3 × 1 m² representative sample plots. The spikes were threshed with a Wintersteiger LD 350 laboratory thresher (Wintersteiger AG, Ried, Austria) to obtain hulled grains, the weight of which was measured. For the quality analyses, the hulled grains or the samples collected from the combine-harvested yield were dehulled by subsequent threshing by the same machine (using sieves to separate grains from hulled grains). Wheat samples were threshed the same way, in one step. In the case of the small-plot trials, combine plot harvesters made the harvesting and threshing in one step. Cleaning, when necessary, was performed with a vibrating sieve and a HALDRUP DC 20 seed cleaner (Haldrup GmbH, Ilshofen, Germany).

In ancient wheats, exact yield measurements can only be made for hulled grain, since the dehulled yield depends greatly on machinery (type, technique, and settings), the targeted processing step, environmental factors (e.g., arid conditions may significantly decrease it), and the characteristics of the species and cultivars. Dehulling might not even be needed at all for the farmer (when the yield is used for marketing, feed, or seed). Therefore, in this study, hulled-grain yields of ancient wheats are compared with the grain yields of naked-grained (hulless) wheats as a natural reference situation. However, based on our measurements, the dehulled-grain yield usually varied between 50 and 65% and 60 and 70% of the hulled weight in einkorn and emmer, respectively.

2.5. Determination of the Protein Content of the Grains

The obtained grain samples of all species were measured with a NIR equipment, Mininfra Scan-T Plus machine (Infracont Kft., Pomáz, Hungary) for grain quality traits, using wheat calibration. Here, we only included the protein values (from the many variables measured), which were proven to be in good agreement with real protein contents, giving a 95–97% correlation with the Kjeldahl method, applied on both emmer and einkorn (previous results not shown here).

2.6. Statistical Analyses

Due to a combination of small-plot and on-farm strip trial systems, the experimental design was complex, i.e., the same group of varieties was not cultivated at all the sites and in all years, and the number of replications also varied. These individual trials can be evaluated separately, but they also provide an opportunity for a review in the present work. For the comparisons between modern and ancient wheat species, the average values for each variety were included in the nonparametric tests (assuming a non-normal distribution). For graphical visualization of the results, the mean values and standard deviations of each variety were used.

Statistical analyses were performed with R version 4.2.2 [51] and the packages ggplot2 [52], ggpubr [53], and FSA [54]. The yield and grain protein content were fitted as response variables in the nonparametric Kruskal–Wallis test, with year and different cereal species fitted as explanatory variables. Differences in response variables between cereal types were calculated using Dunn’s multiple comparisons test, and *p*-values were adjusted using the Holm method. Meanwhile, the differences in the year and grain protein content of each cereal species were calculated using the nonparametric Mann–Whitney Wilcoxon test. The significance levels of tests performed were at a 95% confidence interval.

3. Results and Discussion

3.1. Disease Incidence in Ancient Wheat Trials (2019–2022)

In all tested crop years, there was no single observation of any leaf fungal diseases (powdery mildew, rusts, or leaf blotch) in einkorn at any sites. This was in line with previous findings on the powdery mildew resistance genes identified in einkorn [44]. In

contrast, emmer seemed to be more susceptible to rusts. Stem rust caused a moderate-to-medium infection in one test site (Füzesgyarmat), with a patchy appearance in all three emmer landraces tested, scoring 3–7 on the 0–9 scale, in 2019. In 2020, it infected three of the five emmers in Želiezovce (also rating 3–7), but only one spring emmer, ‘Schwarzer Eschikon’, was susceptible in the Szár location in 2021 (from the 16 emmers and 7 einkorns tested). As this disease benefits from temperatures above 25 °C and thus can affect late-maturing plants more under favourable conditions, this implies that emmers might be occasionally more prone to stem rust, being more susceptible than einkorn.

Other diseases only infected emmer more significantly under conventional cultivation. In the on-station strip trial of Martonvásár, 2019, where the plots received synthetic NPK fertilizers, infection rates from medium resistance to moderate susceptibility (4–7, averaging 5.1 on the 0–9 scale) were reported for leaf rust in most emmers (10 of 11). Also, in this experiment, there was one record of yellow rust (in the emmer ‘Roter’ rating 3). However, at the other locations, which were managed organically, no leaf or yellow rust symptoms were found in that year.

In other years and locations, only insignificant symptoms could be observed. On the organic farm of Szár in 2021, only one emmer landrace ‘Roter’ exhibited slight susceptibility to powdery mildew. Late spring precipitation and the resulting moist conditions of 2022 in Szár allowed an appropriate comparison between modern (winter wheat) and ancient wheats (einkorn, emmer, and spelt) regarding powdery mildew. *Blumeria* spp. infected spelt moderately, averaging a score of 3.5 (according to the Saari–Prescott scale, 0–9). Winter wheat was similarly affected (probably due to the decades of targeted breeding), reaching an average of 2.9. However, emmer and einkorn were resistant to powdery mildew, scoring values of 0.9 and null, respectively (detailed data in Supplement File S1). Other leaf fungal diseases were sporadic and insignificant (e.g., only one variety was affected by yellow rust, both in wheat and in emmer).

These results aligned with previous findings on ancient wheats’ resistance against certain diseases, including powdery mildew, leaf rust, and leaf blotch diseases [13,47]. In one study [11], even the emmer varieties were found to be resistant to usual wheat diseases, which was confirmed for most locations and most years here as well, but with notable exceptions (described above).

Fusarium head blight can be a severe problem for cereals in epidemic years, and 2019 was such a year in Hungary. In Füzesgyarmat, where *Fusarium* infection was the most severe compared to all the test sites that year, the field symptoms of the most infected emmers were still within the range of the most tolerant common wheats grown at the same location (Figure 2a,b). Even the most susceptible emmer landrace, GT 1402 (‘Weisserbehaarter’), had only 786 µg/kg deoxynivalenol (DON) content in the grains (much below the permitted limit of 1250 µg/kg), even though it was lodged to the bare soil, being more exposed to the disease (Table 2). The other two emmer landraces, GT 831 and GT 1400 (‘Blau-emmer’ and ‘Schwarzbehaarter’), had DON levels of only 258 and 218 µg/kg, respectively. These concentrations were minor compared to those very high values reported for winter wheats tested at the same location (Füzesgyarmat) in the same year [4], which can be found in Table 2. In Martonvásár, emmer and einkorn grain DON was below the detection limit or slightly above it. At this site, even in cases where a higher number of emmer spikes became infected, severity (ratio of infected spikelets) was very low, or the opposite; if *Fusarium* spread was high (infecting the whole spike), the incidence (number of infected spikes) was very low, e.g., in the case of the spring emmer (Figure 2c).

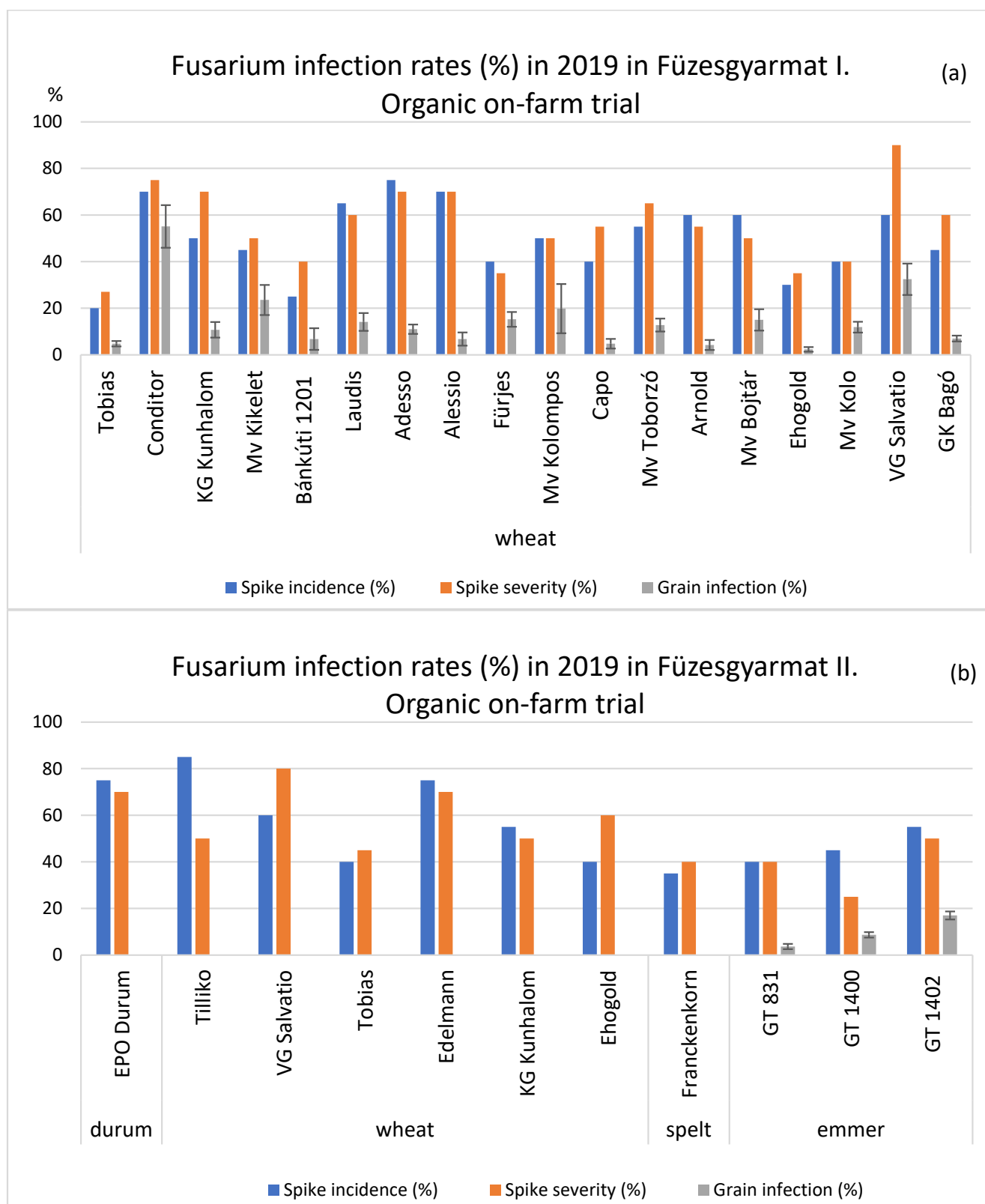


Figure 2. Cont.

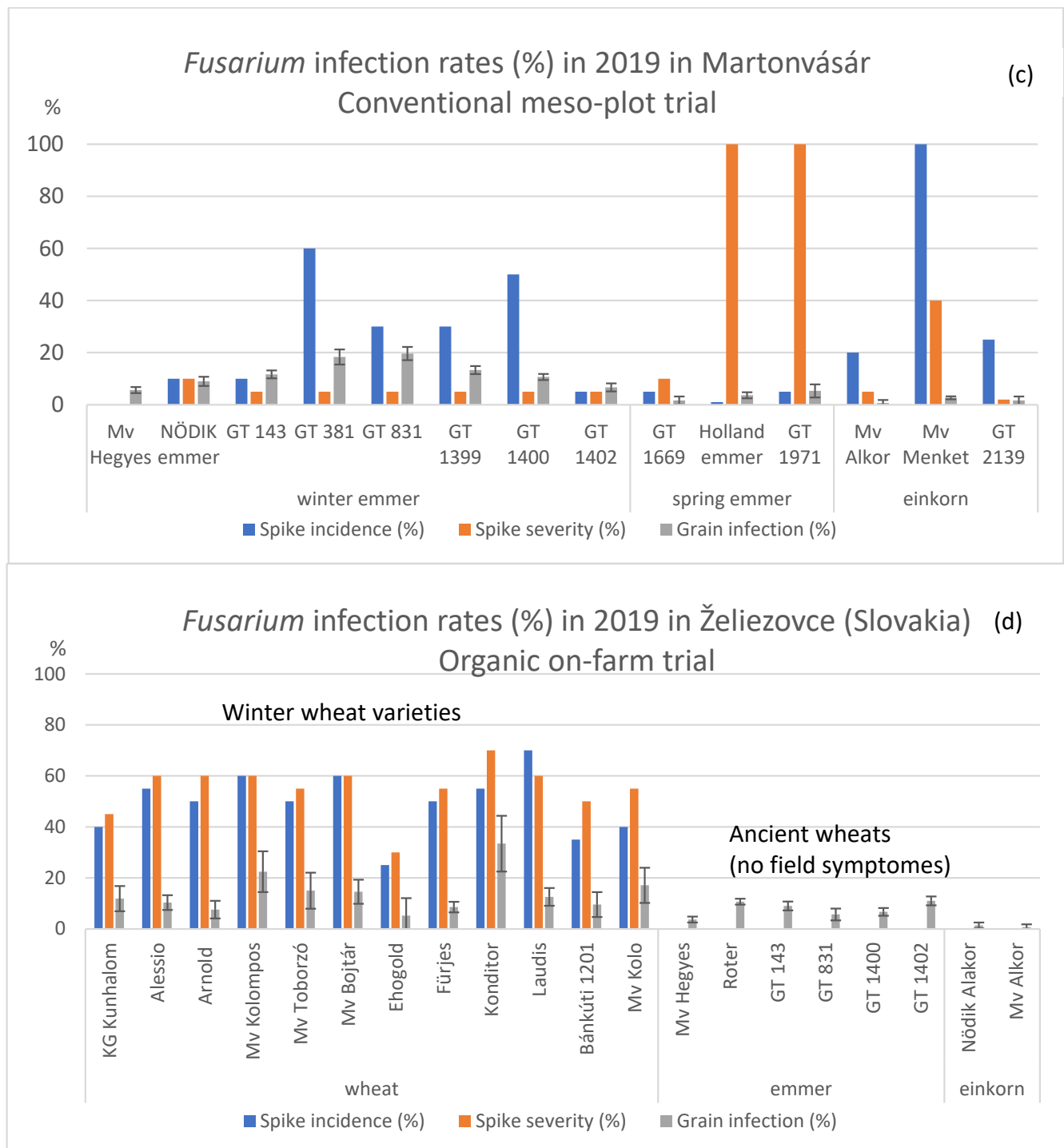


Figure 2. *Fusarium* infection in the epidemic year of 2019 at the experimental sites. Figures (a,b) show the organic on-farm trial of Füzesgyarmat location, (c) refers to the conventional meso-plot trial of Martonvásár, while (d) shows the organic on-farm site of Želiezovce. Species tested: common wheat, durum, spelt, emmer, and einkorn. *Fusarium* spike incidence and severity rates were evaluated in the field for each on-farm cultivar plot, while grain infection rate was measured in three grain subsamples for each cultivar.

Table 2. Grain deoxinivalenol (DON) mycotoxin content of emmer and einkorn landraces and varieties, and selected wheat varieties at various test sites in the epidemic year of 2019.

Wheat			Emmer		Einkorn	
Site	Variety	Sample DON (µg/kg)	Variety/Landrace	Sample DON (µg/kg)	Variety/Landrace	Sample DON (µg/kg)
Martonvásár	Mv Káplár	115	Mv Hegyes	148	GT-2139	n.d.
			Nödik emmer	n.d.	Mv Alkor	n.d.
			GT 143	n.d.	Mv Menket	174
			GT 381	n.d.		
			GT 831	n.d.		
			GT 1399	n.d.		
			GT 1400	n.d.		
			GT 1402	123		
			GT 1669	n.d.		
			GT 1971	n.d.		
			Holland spring emmer	n.d.		
Füzesgyarmat	KG Kunhalom	1677	GT 831	258		
	Arnold	710	GT 1400	218		
	Bánkúti 1201	703	GT 1402	786		
	Capo	1254				
	Conditor	2218				
	Ehogold	2273				
	Fürjes	2465				
	Mv Kikelet	4388				
	Tobias	1504				
Želiezovce	Kunhalom	328				
	Arnold	934				
	Bánkúti 1201	1502				
	Ehogold	789				
	Tobias	430				
	Evina	1291				

n.d. = not detected; detection limit is 100 µg/kg. Permitted limit value is 1250 µg/kg DON for grain samples.

Altogether, field infection rates and grain infection data also confirmed at all sites that both emmer and, especially, einkorn had low susceptibility to *Fusarium* compared to bread wheat (e.g., in Želiezovce, Figure 2d). One single exception was a modern commercial short einkorn variety (bred for intensive farming), the spikes of which exhibited the signs of severe infection by *Fusarium* (but without confirmed substantial DON accumulation). From the experiments conducted so far, it can be stated that emmer and einkorn had better-than-average field resistance to *Fusarium* among tested cereals and, most importantly, they also possessed a low threat of grain DON contamination, even under conditions with high potential *Fusarium* risk. This also means that their consumption, even as a whole-meal product, carries a lower health risk than that of wheat. These findings are in accordance with previous studies on emmer and einkorn being more resistant to *Fusarium* than wheat and spelt [13,46].

Altogether, regarding any kind of disease, no plant protection treatment was needed in either emmer or einkorn against any pathogen, any year, and at any test site, as no on-farm site or small-plot trials were severely affected.

3.2. Weed Occurrence in Modern and Ancient Wheats

In general, the participating farmers of the on-farm locations did not have any severe weed issues in the past years when growing einkorn and emmer as a winter crop. In fact, they were content with the weed-suppression ability of these species. Problems occurred only where major agrotechnological mistakes were made or spring sowing took place (in einkorn) and perennial grass competition was present from early growth (in the case of no-till cultivation). At Szár, where the nutrient conditions were the best out of all the locations, mechanical harrowing in early spring of 2021 solved all emerging weed problems, despite the high weed incidence around the plots. In 2022, no harrowing took place at this trial site, which permitted data collection on the surface weed coverage of ancient and modern wheat plots. The results of the scores (0–5, where 5 = up to 50% coverage) showed that winter wheat had low weed coverage levels (0.68), while spelt, emmer, and einkorn scored, on average, 0.46, 0.60, and 1.07, respectively. These results did not differ statistically, which confirmed the relatively good weed-suppression ability (1 = up to 5% surface coverage) of the tested varieties of all species.

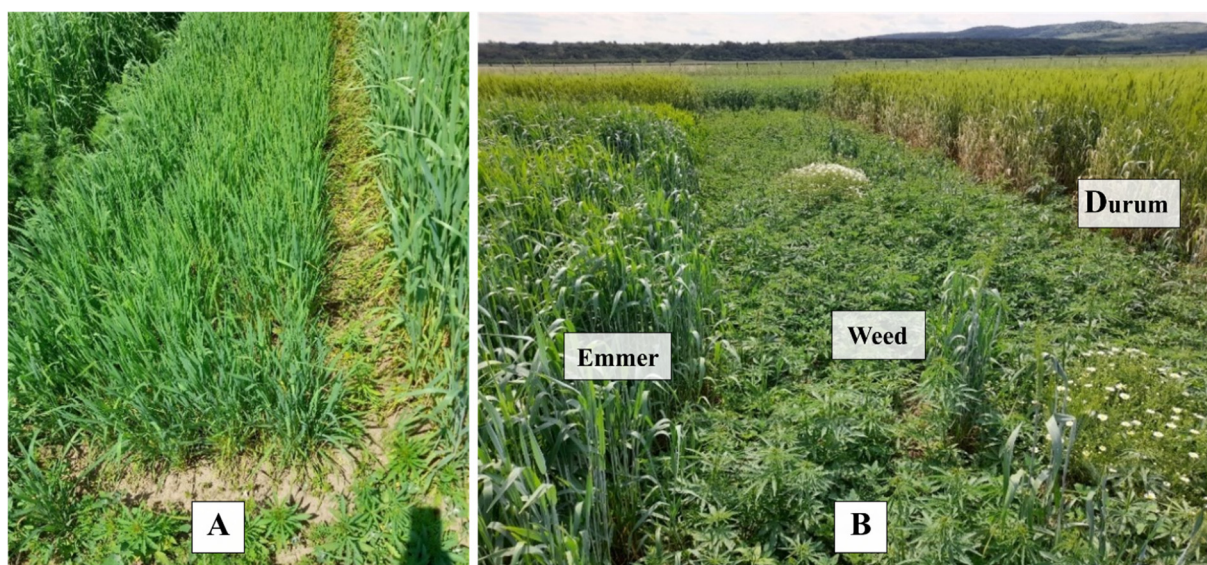


Figure 3. Weed suppression of an einkorn landrace (A), where a bare lane surrounds the plot with restricted weed flora. Impact of cereal leaf beetle (B) emmer plots with no symptoms (left); durum wheat trial suffering great leaf damage from the beetle larvae (right); and weed flora before soil cultivation in the separating lane (middle). Images were taken from the Szár site in 2022.

When talking about weeds, the composition of weed flora is essential, which at the Szár site was predominated by *Cannabis ruderalis* and common poppy (*Papaver rhoeas*), among other less significant species, e.g., field bindweed (*Convolvulus arvensis*), mayweed (*Tripleurospermum* spp.), and sporadic ones, being present in small numbers. A deep-rooting perennial weed, the field thistle (*Cirsium arvense*), had a patchy distribution in certain parts of the experimental site, influencing most of the ancient wheat plots located there, in contrast with the wheat plots located outside these patches (confirmed by visual weed assessment of the cultivation lanes and rows between plots). Especially, emmers appeared to tolerate certain flowering weed plants, such as mayweed (*Tripleurospermum* spp.), by not fully restraining them but rather growing over them. An astonishing example of weed exclusion in einkorn is shown in Figure 3, where the plot was surrounded by approximately 20 cm of a bare lane of soil, suggesting a possible allelopathic interaction. This was in line with other studies investigating allelopathic suppression of the germination of weed species or radish seedlings by ancient wheat plant extracts [48,55]. As the tested wheat varieties

were expected or proved to be adapted to organic cultivation (most were organically bred varieties or recommended for organic farming), this implied a better weed-suppression ability (compared to conventional varieties), which was confirmed here.

In general, the good weed-suppression ability reported here for ancient wheats, emmer, einkorn, and spelt, and the winter wheat varieties adapted to organic cultivation, provides practical field experience to the limited number of previous studies on both ancient and modern wheats [48,49,55].

3.3. Cereal Leaf Beetle Infestation

Cereal leaf beetles (*Oulema melanopus*) caused a severe infection in 2022 in the organic test site of Szár. Although the beetle larvae were not evenly distributed over the whole experiment, they exhibited a clear host preference. Some plots of winter wheat and spelt were dramatically infected, even reaching a score of 9 (from 0 to 10), with average values of 3.4 on the infected wheat plots (and 2.0 for all, infected and not infected) and 3.9/2.7 for spelt (infected/all plots counted). No single incidence of leaf beetle occurrence was, however, recorded for any of the emmer or einkorn accessions, although they were neighbouring and surrounding the infested spelt plots and opposite to the most infected durum trials (the results of which are not presented in this study) (for details see Supplement File S1). The flying female beetles refused to lay their eggs on these ancient wheat plants, confirming that these two species are unattractive to this dangerous pest, which can damage host plant leaves severely, decreasing the photosynthetic capacity dramatically [35,37]. Although *Oulema* beetles feed on a wide range of species, including wild and cultivated plants, no reported mention of emmer or einkorn was found among their hosts, despite the rich collection of more than 20 species, also including spelt (e.g., [56,57]), and the present work confirmed their avoidance. Leaf pubescence was identified as a source of resistance to this beetle [57,58], which may explain the avoidance observed in emmer. However, this mechanism does not clarify why einkorn, despite being glabrous, was not colonized. To understand this, further study is needed on whether the host–pest signalling or metabolic processes are also involved. Interestingly, ancient wheats were also reported to be less susceptible to storage pests [59]. All these results indicate that emmer and einkorn possess exceptional traits that make them particularly suitable for pesticide-free agriculture. In the case of emmer, these findings further support its potential use in targeted breeding programmes aimed at developing more resistant materials, such as durum cultivars, taking advantage of their close genetic relatedness.

3.4. Yield Performance of Modern vs. Ancient Wheats at the Organic Farm Sites (2019–2022)

To determine what relation emmer and einkorn yields may have with those of modern wheats, data from the on-farm sites where winter wheat was also tested were compared to those of emmer and einkorn (Figure 4a, for more details see Supplement File S2). In Želiezovce, one of the sites with the best cropping conditions, the mean grain yields of wheat, emmer, and einkorn were 6.14, 2.96, and 2.51 t/ha in 2019, 5.78, 4.48, and 3.44 t/ha in 2020, and 5.45, 3.01, and 2.53 t/ha in 2021, respectively. In Füzesgyarmat (with low nutrient supply levels), grain yields of wheat, emmer, and einkorn were rather similar: 2.94, 3.03, and 3.16 t/ha in 2021. Under the lowest-performing conditions of Pásztó, wheat, emmer, and einkorn yields were 1.02, 1.07, and 1.45 in 2020, resp., and 1.36 and 1.69 t/ha for emmer and einkorn in 2021 (Figure 4a, Supplement File S2). The results clearly show that under highly productive conditions, common wheat outperformed ancient wheats, though in some crop years (due to drought, e.g., in Želiezovce in 2020), the yield gap may considerably decrease. However, under low nutrient supply levels, the yield difference may collapse between winter wheat and ancient wheats. These results confirmed

previous findings, which reported greater yield stability for ancient wheats under poor growing conditions [8].



Figure 4. Modern wheat grain yield and ancient wheat hulled-grain yield (a) and grain protein content (b) in the organic on-farm experiments and the small-plot trial site Szár, in years 2019–2022. Abbreviations of locations: SZR = Szár, Zel = Želiezovce, FGY = Füzesgyarmat, and PAS = Pásztó. At Szár in 2021, the numbers of cultivars tested were 21, 6, 16, and 7 for wheat, spelt, emmer, and einkorn, while in 2022, there were 26, 12, 16, and 7 accessions, respectively. In Želiezovce, the numbers of wheat, emmer, and einkorn cultivars were 16, 6, and 2 in 2019; 27, 4, and 4 in 2020; and 21, 5, and 1 in 2021, respectively. The numbers of the related same species were 19, 5, and 3 in Füzesgyarmat in 2021 and 10, 2, and 2 in Pásztó in 2020, respectively.

The three-replication, small-plot organic variety tests set up first in the crop year 2020/2021 at Szár allowed comparisons between a wide range of modern and ancient wheat cultivars. Although this crop year lacked precipitation from March to the very end of May, this location offered one of the best nutritional supplies for the plants among the test sites. After soybean as a pre-crop, not surprisingly, the early-maturing winter wheat yielded exceedingly high, 7.49 t/ha grains (Figure 4a). Einkorn, winter and spring emmers, and spelt produced an average of 2.76, 2.93, 2.72, and 3.53 t/ha hulled-grain yield, respectively. Emmer and einkorn yields did not differ statistically from each other.

In 2022, after a long, dry winter and spring period, the April rains in Szár came at the very last minute, so that the plants could partly compensate for the preceding extreme drought. Nevertheless, winter wheat produced an average grain yield of 7.50 t/ha (Figure 4a). For spelt, the average hulled-grain yield was 4.60 t/ha, while winter and spring emmers made 5.03 and 4.14, and einkorn had a 3.77 t/ha yield on average. This year, only winter wheat differed significantly from the rest of the species. Interestingly, in 2022, the hulled-grain yields of the best-yielding ancient wheats were comparable to those of the lowest-yielding winter wheats.

Comparisons between the two crop years in Szár revealed that although winter wheat yield was unchanged, significant differences were recorded for einkorn and emmer yields, both producing higher yields in 2022 (Mann–Whitney Wilcoxon test, $p = 0.011$ and $p < 0.001$, respectively).

Based on the two-year datasets combined, it can be concluded that yield differences were significant between winter wheat and ancient wheats (Kruskal–Wallis test, $p < 0.001$). There were, however, no significant differences between einkorn, emmer, and spelt. (More details on statistical analyses are given in Supplement File S3).

Altogether, taking into account on-farm results and the small-plot experiment, ancient wheats, and especially einkorn and emmer, could, on average, produce a hulled-grain yield of about half the grain yield of winter wheat under the best soil conditions. While under low nutrient supply levels or even poor conditions, they could yield similar values to winter wheat. Still, even so, they could only rarely go above common wheat (depending on the varieties). Cultivation of emmer and einkorn has, therefore, a greater potential in locations where wheat can, on average, yield only up to 3–5 t/ha, as on these sites, the two ancient species can produce more comparable yields to those of common wheat.

The yield ratio of einkorn and emmer compared to wheat, found in the present work, was in line with other data that reported on, e.g., emmers, the grain yield of which reached 58% of the yield level of the control bread wheats [11].

3.5. Yield Variation in Emmer and Einkorn Within the Whole Participatory Trial System (2019–2022)

In addition to the detailed findings shown above, the yield values obtained for emmer and einkorn landraces in the whole on-farm network, in all locations, gave similar results. They varied from a few hundred kg (on the most extreme soils in Bugac, with running sand combined with extreme drought in 2021, where the minimum, maximum, and mean values for emmer and einkorn yield were 172/477/338 and 286/616/400 kg/ha, resp.) up to exceeding 4.4 t/ha in einkorn and 4.7 t/ha in emmer on the best on-farm soils. Under low-input and medium (climatic and soil) conditions, yields were usually obtained between 1.9 and 4.3 and 1.5 and 4.2 t/ha in emmer and einkorn, respectively. These results align with previous findings [8,9,12,13]. However, einkorn tended to produce slightly higher yields than emmer under poor, marginal conditions (e.g., in Pásztó and Bugac), while emmer had slightly higher potential under better-than-medium conditions.

3.6. Grain Protein Content of Ancient and Modern Wheats (2019–2022)

In the small-plot organic trial of Szár, NIR analyses showed that ancient wheats had much higher grain protein content (15% and up) than winter wheat (up to 15%, Figure 4b), which was in line with previous research [13]. However, these measurements also confirmed that 2021 was an unusually dry crop year for cereals, as the protein values were extremely high, probably as a result of forced maturation due to the heavy drought. Grain protein content averaged at 22.5, 17.9, 19.5, and 18.7% for einkorn, winter emmer, spring emmer, and spelt, respectively, while winter wheat had 12.9%. In 2022, these values were 16.8, 16.0, 19.2, and 17.6 for ancient wheats, respectively, and 13.5% for winter wheat (Figure 4b), indicating that growth conditions were more regular that year. Kruskal–Wallis Dunn tests proved significant differences between winter wheat and other ancient species in both years. Ancient wheat species, however, did not differ significantly from each other in either year. The most extreme values were found in einkorn, which varied the most in both years, having outstandingly high SD values (2.38 and 2.27 in 2021 and 2022).

In the other on-farm test sites, although protein values were somewhat lower than those of Szár, common wheat had the lowest values in all cases and crop years compared to emmer and einkorn (Figure 4b). Altogether, einkorn and emmer had a minimum of 0.4 and 0.7%, a maximum of 9.5 and 5.3%, and, on average, both had 2.6% higher protein content than common wheat.

As was suggested before [28], the high protein values of ancient wheats could be attributed to their lower yields. Common wheat indeed had better protein yield than ancient wheats—this was also the case here, as winter wheats had approximately double the high yields and a few percent lower protein content than ancient wheats had. This, however, does not lessen the high nutritional value of ancient wheats. Interestingly, under the poorest conditions of the Pásztó location, emmer and einkorn tended to have both higher yield and higher protein content than common wheat (Figure 4a,b). Here, 8 of 10 wheat varieties ranked after emmer or einkorn in yield.

It is also important to note that in the small-plot trial, only those wheat varieties were included that were most suitable for organic conditions (some were even organic varieties or proven, recommended ones for organic farming). There is, however, a massive amount of other registered winter wheat varieties, especially conventional ones with poor weed-suppression ability, weak disease resistance, or low stress tolerance, which would most probably perform significantly worse in a pesticide-free production system than the results obtained here, and thus would be closer to the ancient wheats in yield, especially under moderate soil conditions.

Between the two crop years, 2021 and 2022, significant differences were found in the grain protein values for all species (Mann–Whitney Wilcoxon test $p = 0.005, 0.005, 0.031$, and 0.023 for einkorn, emmer, spelt, and wheat, respectively). Not surprisingly, the overall protein values obtained in this experiment were in accordance with the literature data [1,13,15–19], confirming that einkorn, emmer, and spelt indeed have considerably higher protein content compared to common wheat, when cultivated in the same place. More details on statistical analyses are given in Supplement File S3).

4. Conclusions

Sustainable agriculture seeks to balance productivity with environmental and social responsibility, contrasting with conventional high-input systems and aligning closely with the principles of organic farming. It emphasizes the efficient use of natural resources, reduced dependence on non-renewable inputs such as synthetic fertilizers and pesticides, and the enhancement of ecosystem services including soil fertility, biodiversity, and water conservation. The present study aimed to provide a more sustainable alternative for both or-

ganic and low-input farming by evaluating two ancient wheat species, emmer and einkorn, as potential candidates for sustainable farming. Here we summarized four years' results, comparing the cultivation of ancient and modern wheats, taking into account various aspects, including weed suppression, resistance to diseases, pest infestation, parameters of grain yield and quality. The results indicate that under favourable growing conditions, emmer and einkorn can produce, as a hulled-grain yield, at almost about half of the yield of modern wheats adapted to organic farming. However, in more challenging years or under low nutrient supply, they can achieve similar yield levels (when comparing hulled to hullless grain). However, choosing the highest-yielding landrace or variety (or even species) can further increase yield performance compared to winter wheat at a given site. The most valuable features of einkorn and emmer include weed-suppression ability, good or excellent (in einkorn) resistance to various diseases (even to *Fusarium* head blight and related DON mycotoxin accumulation), an unattractive character to cereal leaf beetle, and a very high grain protein content, compared to common wheat. These findings highlight the potential of these resistance traits to be exploited in targeted breeding programmes—for instance, by incorporating emmer into crossing schemes aimed at developing durum wheat cultivars with enhanced resistance to *Fusarium* infections.

The cultivation of emmer and einkorn, however, cannot be successful without profitability. As under more-productive conditions, they may yield considerably less than winter wheat (and because dehulling usually involves a 30–40% weight loss), the yield gap can be a crucial limitation to their cultivation, even under pesticide-free cropping systems. This, however, has lately been compensated by the 2–2.5 times higher market price of emmer and einkorn compared to that of common wheat. Yet, the current price difference might not be available in the long term, considering the uncertainties of the organic market in response to economic or humanitarian crises. Nevertheless, under more limiting cropping conditions and more frequent extreme climatic events, emmer and einkorn's advantages become more apparent. Here, they pose a viable alternative for pesticide-free cereal producers and may generate more stable and higher-quality produce than common wheat cultivars.

Higher levels of product processing can also make emmer and einkorn cultivation more profitable. Therefore, product development from ancient wheats is also addressed within the on-farm living lab methodology, through the active collaboration of researchers, participating farmers, processors, and producers to build new value chains. Some landraces were found to be exceptionally good for bread-making due to their taste and higher grain quality, but pastries, pasta, and other traditional food-processing directions are also tested. To promote their spread in the market, we also targeted new innovations: the development of dairy-free vegan substitutes for milk and fermented products (e.g., yoghurt, kefir, and cheese) and artisan einkorn and emmer beer.

In summary, linking the past and the future, with this comprehensive analysis of ancient and modern wheats, we provide evidence that the most ancient wheats, emmer and einkorn, are still suitable for production under low-input and organic farming conditions, and are especially suitable for pesticide-free agriculture.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su172210088/s1>; File S1: Disease, pest, and weed scores in Szár, 2022; File S2: Grain and hulled-grain yields (minimum, maximum, and mean values) of winter wheat and emmer and einkorn in the on-farm experiments, 2019–2021; File S3: Statistical analyses with graph 1 (Grain and hulled-grain yield comparisons between modern and ancient wheats, Szár 2021–2022) and Graph 2 (Grain protein content (%) comparisons between modern and ancient wheats, Szár 2021–2022).

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References

- Geisslitz, S.; Longin, C.F.H.; Scherf, K.A.; Koehler, P. Comparative Study on Gluten Protein Composition of Ancient (Einkorn, Emmer and Spelt) and Modern Wheat Species (Durum and Common Wheat). *Foods* **2019**, *12*, 409. [\[CrossRef\]](#) [\[PubMed\]](#)
- Hollósi, A.Z. Ósi Búzafajok Szerepe az Ökológiai Gazdálkodásban. Diploma Thesis, MATE Tessedik Campus, Szarvas, Hungary, 2022; p. 66. (In Hungarian).
- Lammerts van Bueren, E.T.; Jones, S.S.; Tamm, L.; Murphy, K.M.; Myers, J.R.; Leifert, C.; Messmer, M.M. The need to breed crop varieties suitable for organic farming, using wheat, tomato and broccoli as examples: A review. *NJAS Wagening J. Life Sci.* **2011**, *58*, 193–205. [\[CrossRef\]](#)
- Földi, M.; Bencze, S.; Hertelendy, P.; Veszter, S.; Kovács, T.; Drexler, D. Farmer involvement in agro-ecological research: Organic on-farm wheat variety trials in Hungary and the Slovakian upland. *Org. Agric.* **2021**, *12*, 293–305. [\[CrossRef\]](#)
- Brown, T.A.; Jones, M.K.; Powell, W.; Allaby, R.G. The complex origins of domesticated crops in the Fertile Crescent. *Trends Ecol. Evol.* **2009**, *24*, 103–109. [\[CrossRef\]](#) [\[PubMed\]](#)
- Gyulai, F. *Archaeobotany in Hungary: Seed, Fruit, Food and Beverages Remains in the Carpathian Basin: An Archaeobotanical Investigation of Plant Cultivation and Ecology from the Neolithic until the Late Middle Ages*; Archaeolingua: Budapest, Hungary, 2010; p. 479.
- Biradar, S.S.; Yashavanthakumar, K.J.; Navathe, S.; Reddy, U.G.; Vijendra, S.; Baviskar, K.; Gopalareddy, K.; Lamani, K.; Desai, S.A. Dicoccum Wheat: Current Status and Future Perspectives. In *New Horizons in Wheat and Barley Research*; Kashyap, P.L., Gupta, V., Gupta, O.M., Sendhil, R., Gopalareddy, K., Jasrotia, P., Singh, P.G., Eds.; Springer: Singapore, 2022. [\[CrossRef\]](#)
- Rachoń, L.; Bobryk-Mamczarz, A.; Kiełtyka-Dadasiewicz, A. Hulled wheat productivity and quality in modern agriculture against conventional wheat species. *Agriculture* **2020**, *10*, 275. [\[CrossRef\]](#)
- Castagna, R.; Borghi, B.; Di Fonzo, N.; Heun, M.; Salamini, F. Yield and related traits of einkorn (*T. monococcum* ssp. *monococcum*) in different environments. *Eur. J. Agron.* **1995**, *4*, 371–378. [\[CrossRef\]](#)
- Troccoli, A.; Codianni, P. Appropriate seeding rate for einkorn, emmer, and spelt grown under rainfed condition in southern Italy. *Eur. J. Agron.* **2005**, *22*, 293–300. [\[CrossRef\]](#)
- Konvalina, P.; Capouchová, I.; Stehno, Z.; Moudrý, J. Differences in yield parameters of emmer in comparison with old and new varieties of bread wheat. *Afr. J. Agric. Res.* **2012**, *7*, 986–992. [\[CrossRef\]](#)
- Marino, S.; Tognetti, R.; Alvino, A. Crop yield and grain quality of emmer populations grown in central Italy, as affected by nitrogen fertilization. *Eur. J. Agron.* **2009**, *31*, 233–240. [\[CrossRef\]](#)
- Bencze, S.; Makádi, M.; Aranyos, T.J.; Földi, M.; Hertelendy, P.; Mikó, P.; Bosi, S.; Negri, L.; Drexler, D. Re-Introduction of Ancient Wheat Cultivars into Organic Agriculture—Emmer and Einkorn Cultivation Experiences under Marginal Conditions. *Sustainability* **2020**, *12*, 1584. [\[CrossRef\]](#)

14. Abdel-Aal, E.S.M.; Hucl, P. Amino acid composition and In vitro protein digestibility of selected ancient wheats and their end products. *J. Food Compos. Anal.* **2002**, *15*, 737–747. [\[CrossRef\]](#)
15. Brandolini, A.; Hidalgo, A.; Moscaritolo, S. Chemical composition and pasting properties of einkorn (*Triticum monococcum* L. subsp. *Monococcum*) whole meal flour. *J. Cer. Sci.* **2008**, *47*, 599–609. [\[CrossRef\]](#)
16. Dhanavath, S.; Rao, U.J. Nutritional and nutraceutical properties of *Triticum dicoccum* wheat and its health benefits: An overview. *J. Food Sci.* **2017**, *82*, 2243–2250. [\[CrossRef\]](#)
17. Arzani, A. Emmer (*Triticum turgidum* spp. *dicoccum*) Flour and Breads. In *Flour and Breads and Their Fortification in Health and Disease Prevention*; Preedy, V.R., Watson, R.R., Patel, V.B., Eds.; Elsevier: Amsterdam, The Netherlands, 2011; pp. 69–78. ISBN 978-0-12-380886-8.
18. Hidalgo, A.; Brandolini, A. Nutritional properties of einkorn wheat (*Triticum monococcum* L.). *J. Sci. Food Agric.* **2014**, *94*, 601–612. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Akar, T.; Cengiz, M.F.; Tekin, M. A comparative study of protein and free amino acid contents in some important ancient wheat lines. *Qual. Assur. Saf. Crops Foods* **2019**, *11*, 191–200. [\[CrossRef\]](#)
20. Chrenková, M.; Gálová, Z.; Čerešňáková, Z.; Sommer, A. Nutritional and biological value of spelt wheat. *Acta Fytotech. Et Zootech* **2001**, *4*, 191–193.
21. Wójtowicz, A.; Oniszczyk, A.; Kasprzak, K.; Olech, M.; Mitrus, M.; Oniszczyk, T. Chemical composition and selected quality characteristics of new types of precooked wheat and spelt pasta products. *Food Chem.* **2020**, *309*, 125673. [\[CrossRef\]](#)
22. Tran, K.D.; Konvalina, P.; Capouchova, I.; Janovska, D.; Lacko-Bartošová, M.; Kopecky, M.; Tran, P.X.T. Comparative study on protein quality and rheological behavior of different wheat species. *Agronomy* **2020**, *10*, 1763. [\[CrossRef\]](#)
23. Biel, W.; Jaroszewska, A.; Stankowski, S.; Sobolewska, M.; Kępińska-Pacelik, J. Comparison of yield, chemical composition and farinograph properties of common and ancient wheat grains. *Eur. Food Res. Technol.* **2021**, *247*, 1525–1538. [\[CrossRef\]](#)
24. Lachman, J.; Orsák, M.; Pivec, V.; Jířů, K. Antioxidant activity of grain of einkorn (*Triticum monococcum* L.), emmer (*Triticum dicoccum* Schuebl [Schrack]) and spring wheat (*Triticum aestivum* L.) varieties. *Plant Soil Environ.* **2012**, *58*, 15–21. [\[CrossRef\]](#)
25. Zrčková, M.; Capouchová, I.; Paznocht, L.; Marine, E.; Dvůrák, P.; Konvalina, P.; Janovská, D.; Orsák, M.; Bečková, L. Variation of the total content of polyphenols and phenolic acids in einkorn, emmer, spelt and common wheat grain as a function of genotype, wheat species and crop year. *Plant Soil Environ.* **2019**, *65*, 260–266. [\[CrossRef\]](#)
26. Barański, M.; Lacko-Bartošová, M.; Rembalkowska, E.; Lacko-Bartošová, L. The effect of species and cultivation year on phenolic acids content in ancient wheat. *Agronomy* **2020**, *10*, 673. [\[CrossRef\]](#)
27. Şahin, Y.; Yıldırım, A.; Yücesan, B.; Zencirci, N.; Erbayram, Ş.; Gürel, E. Phytochemical content and antioxidant activity of einkorn (*Triticum monococcum* ssp. *monococcum*), bread (*Triticum aestivum* L.), and durum (*Triticum durum* Desf.) wheat. *Progr. Nutr.* **2018**, *19*, 450–459. [\[CrossRef\]](#)
28. Piergiovanni, A.R.; Rizzi, R.; Pannacciulli, E.; Della Gatta, C. Mineral composition in hulled wheat grains: A comparison between emmer (*Triticum dicoccon* Schrank) and spelt (*T. spelta* L.) accessions. *Int. J. Food Sci. Nutr.* **1997**, *48*, 381–386. [\[CrossRef\]](#)
29. Zhao, F.J.; Su, Y.H.; Dunham, S.J.; Rakszegi, M.; Bedő, Z.; McGrath, S.P.; Shewry, P.R. Variation in mineral micronutrient concentrations in grain of wheat lines of diverse origin. *J. Cereal Sci.* **2009**, *49*, 290–295. [\[CrossRef\]](#)
30. Čurná, V.; Lacko-Bartošová, M. Chemical composition and nutritional value of emmer wheat (*Triticum dicoccon* Schrank): A review. *J. Cent. Eur. Agric.* **2017**, *18*, 117–134. [\[CrossRef\]](#)
31. Dinu, M.; Whittaker, A.; Pagliai, G.; Benedettelli, S.; Sofi, F. Ancient wheat species and human health: Biochemical and clinical implications. *J. Nutr. Biochem.* **2018**, *52*, 1–9. [\[CrossRef\]](#)
32. Iacomino, G.; Aufiero, V.R.; Stasio, L.D.; Picascia, S.; Iannaccone, N.; Giardullo, N.; Troncone, R.; Gianfrani, C.; Mamone, G.; Mazzarella, G. *Triticum monococcum* amylase trypsin inhibitors possess a reduced potential to elicit innate immune response in celiac patients compared to *Triticum aestivum*. *Food Res. Int.* **2021**, *145*, 110386. [\[CrossRef\]](#)
33. Birinyi, Z.; Réder, D.; Diós, Á.; Korponay-Szabó, I.R.; Hunyadi-Gulyás, É.; Florides, C.G.; Juhász, A.; Gell, G. Immunoanalytic investigation of grain proteins antigenic for celiac disease patients in an einkorn collection. *Food Chem.* **2022**, *371*, 131148. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Güllü, M.; Gözüağık, C.; Konuksal, A. Wheat insect pests. In *Advances in Wheat Breeding*; Zencirci, N., Altay, F., Baloch, F.S., Nadeem, M.A., Ludidi, N., Eds.; Springer: Berlin/Heidelberg, Germany, 2024; pp. 391–451. [\[CrossRef\]](#)
35. Buntin, G.D.; Flanders, K.L.; Slaughter, R.W.; DeLamar, Z.D. Damage loss assessment and control of the cereal leaf beetle (*Coleoptera: Chrysomelidae*) in winter wheat. *J. Econ. Entomol.* **2004**, *97*, 374–382. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Oregon State University Extension. Cereal Leaf Beetles Pose Threat to Grain Crops. 2023. Available online: <https://extension.oregonstate.edu/crop-production/field-crops/cereal-leaf-beetles-pose-threat-grain-crops> (accessed on 15 September 2025).
37. Kher, S.; Dosdall, L.M.; Carcamo, H. The cereal leaf beetle: Biology, distribution and prospects for control. *Prairie Soils Crops* **2011**, *4*, 32–41. Available online: https://www.researchgate.net/publication/251472934_The_Cereal_Leaf_Beetle_Biology_Distribution_and_Prospects_for_Control (accessed on 15 September 2025).

38. Keszthelyi, S.; Hoffmann, R.; Lukács, H. Objective assessment of the damage caused by *Oulema melanopus* in winter wheat with intensive cultivation technology under field conditions. *AgriEngineering* **2024**, *6*, 4538–4548. [\[CrossRef\]](#)
39. Sicker, D.; Frey, M.; Schulz, M.; Gierl, A. Role of naturalbenzoxazinones in the survival strategy of plants. *Int. Rev. Cytol.* **2000**, *198*, 319–346. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Grausgruber, H.; Scheiblaue, J.; Schönlechner, R.; Ruckenbauer, P.; Berghofer, E. Variability in chemical composition and biologically active constituents of cereals. In *Genetic Variation for Plant Breeding, Proceedings of the 17th EUCARPIA, General Congress, Tulln, Austria, 8–11 September 2004*; Vollmann, J., Grausgruber, H., Ruckenbauer, P., Eds.; University of Natural Resources and Applied Life Sciences: Vienna, Austria, 2004; pp. 23–26.
41. Ruibal-Mendieta, N.L.; Delacroix, D.L.; Mignolet, E.; Pycke, J.M.; Marques, C.; Rozenberg, R.; Petitjean, G.; Habib-Jiwan, J.L.; Meurens, M.; Quetin-Leclercq, J.; et al. Spelt (*Triticum aestivum* ssp. *spelta*) as a source of breadmaking flours and bran naturally enriched in oleic acid and minerals but not phytic acid. *J. Agric. Food Chem.* **2005**, *53*, 2751–2759. [\[CrossRef\]](#)
42. Ciccoritti, R.; Pasquini, M.; Sgrulletta, D.; Nocente, F. Effect of 5-n-alkylresorcinol extracts from durum wheat whole grain on the growth of *Fusarium* head blight (FHB) causal agents. *J. Agric. Food Chem.* **2015**, *63*, 43–50. [\[CrossRef\]](#)
43. Pedrazzani, C.; Vanara, F.; Bhandari, D.R.; Bruni, R.; Spengler, B.; Blandino, M.; Righetti, L. 5-n-Alkylresorcinol profiles in different cultivars of einkorn, emmer, spelt, common wheat, and tritordeum. *J. Agric. Food Chem.* **2021**, *69*, 14092–14102. [\[CrossRef\]](#)
44. Yao, G.; Zhang, J.; Yang, L.; Xu, H.; Jiang, Y.; Xiong, L.; Zhang, C.; Zhang, Z.; Ma, Z.; Sorrells, M.E. Genetic mapping of two powdery mildew resistance genes in einkorn (*Triticum monococcum* L.) accessions. *Theor. Appl. Genet.* **2007**, *114*, 351–358. [\[CrossRef\]](#)
45. Zaharieva, M.; Ayana, N.G.; Al Hakimi, A.; Misra, S.C.; Monneveux, P. Cultivated emmer wheat (*Triticum dicoccon* Schrank), an old crop with promising future: A review. *Genet. Resour. Crop Evol.* **2010**, *57*, 937–962. [\[CrossRef\]](#)
46. Góral, T.; Ochodzki, P. *Fusarium* head blight resistance and mycotoxin profiles of four *Triticum* species genotypes. *Phytopathol. Mediterr.* **2017**, *56*, 175–186. [\[CrossRef\]](#)
47. Konvalina, P.; Capouchová, I.; Stehno, Z.; Moudrý, J. Agronomic characteristics of the spring forms of the wheat landraces (einkorn, emmer, spelt, intermediate bread wheat) grown in organic farming. *J. Agrobiol.* **2010**, *27*, 9–17. [\[CrossRef\]](#)
48. Fatholahi, S.; Karimmojeni, H.; Ehsanzadeh, P. Phenolic compounds and allelopathic activities of ancient emmer wheats: Perspective for non-chemical weed control scenarios. *Acta Physiol. Plant* **2020**, *42*, 135. [\[CrossRef\]](#)
49. Emődi, A.; Tirczka, I.; Hartman, M.; Dobólyi, C.; Sebők, F.; Gyulai, F. Two ancient wheat species, possibilities for the production of einkorn and emmer in organic farming. *Ann. Fac. Eng. Hunedoara* **2014**, *12*, 43.
50. Saari, E.E.; Prescott, L.M. A scale for appraising the foliar intensity of wheat diseases. *Plant Dis. Rep.* **1975**, *59*, 377–380.
51. R Core Team. *R: A Language and Environment for Statistical Computing*. R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing: Vienna, Austria, 2022.
52. Wickham, H. *ggplot2: Elegant Graphics for Data Analysis*; Springer: New York, NY, USA, 2009. [\[CrossRef\]](#)
53. Kassambara, A. Ggpubr: “ggplot2” Based Publication Ready Plots. 2020. Available online: <https://cran.r-project.org/package=ggpubr> (accessed on 1 September 2023).
54. Ogle, D.H.; Doll, J.C.; Wheeler, P.; Dinno, A. FSA: Fisheries Stock Analysis. 2022. Available online: <https://github.com/fishR-Core-Team/FSA> (accessed on 1 September 2023).
55. Kitis, Y.E.; Tekin, M.; Akar, T. The allelopathic effects of turkish hulled wheat lines on germination of *Amaranthus retroflexus* L. and *Lolium perenne* L. seeds. *Uluslararası Tarım ve Yaban Hayatı Bilim. Dergisi.* **2021**, *7*, 56–62. [\[CrossRef\]](#)
56. Hodgson, E.W.; Evans, E.W. Cereal Leaf Beetle. Utah Pests Fact Sheet. Utah State University Extension and Utah Plant Pest Diagnostic Laboratory ENT-84-07PR. 2007. p. 4. Available online: https://digitalcommons.usu.edu/extension_curall/874 (accessed on 15 September 2025).
57. Glogoza, P. Cereal Leaf Beetle *Oulema melanopus* (L.) (Coleoptera: Chrysomelidae). NDSU Extension, E1230. North Dakota State University, Fargo, North Dakota. 2022. p. 2. Available online: <https://www.ndsu.edu/agriculture/sites/default/files/2022-03/e1230.pdf> (accessed on 15 September 2025).
58. Papp, M.; Mesterházy, Á. Resistance of winter wheat to cereal leaf beetle (Coleoptera: Chrysomelidae) and bird cherry-oat aphid (Homoptera: Aphididae). *J. Econ. Entomol.* **1996**, *89*, 1649–1657. [\[CrossRef\]](#)
59. Gałęcki, R.; Bakuła, T.; Wojtacki, M.; Żuk-Gołaszewska, K. Susceptibility of ancient wheat species to storage pests *Sitophilus granarius* and *Tribolium confusum*. *J. Stored Prod. Res.* **2019**, *83*, 117–122. [\[CrossRef\]](#)

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