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# Effects of Nutrient Supply and Seed Size on Germination Parameters and Yield in the Next Crop Year of Winter Wheat (*Triticum aestivum* L.)

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**Abstract:** Winter wheat is one of the most important crops globally and also in Hungary. Hungary has excellent crop production potential including seed production. The aim of our experiment is to determine the effects of different amounts and proportions of nutrients and those of the seed size of winter wheat in laboratory seed tests on the seed parameters (germination percentage, germination power, seedling health and vigour), as well as in field tests of the seed parameters (emergence percentage and yield of next crop year). Laboratory seed tests of winter wheat variety GK Petur were conducted with seeds that underwent ten nutrient treatments and of three seed size fractions over four crop years, together with field experiments in three growing seasons. Compared to the untreated control group, N treatments significantly decreased the health of the seedlings in the next generation of winter wheat. PK treatments without N increased the germination percentage, vigour value and emergence percentage significantly, but the health of the seedlings decreased. In contrast, NPK treatments with a ratio of 2:1:1 improved all the tested parameters compared to those of the control group. The increase in seed sizes significantly increased the germination power, seedling health, vigour value, emergence percentage and the yield of the next crop year. It can be concluded that the factors of nutrient supply, crop year of the seed production and the seed size significantly influence the quality of the seed (germination percentage, germination power, seedling health, vigour and emergence percentage), thus also the yield of the next generation.

**Keywords:** winter wheat; nutrient supply; seed size; seed test; germination; vigour; emergence; yield



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## 1. Introduction

Winter wheat is one of the most widely grown crops globally [1]. Its adaptability allows it to be grown in a wide range of soil and climate conditions [2–5]. It is the most important cereal, the source of food for most people around the world [6–8] and a feed material [9,10]. It is used to make bread and pasta, but it can also be used to produce cereals and malt [9,11]. Hungary has excellent crop production potentials [12,13], and its seed production and seed trade are significant. In Hungary, winter wheat is grown on nearly 1 million hectares, while wheat seeds are produced on 24–27 thousand hectares [14]. Winter wheat seed produced in Hungary is mostly sown by domestic farmers, but the income from exports is also significant [15]. Unfortunately, farmers use certified seeds only on 25–28% of the winter wheat sowing areas, and it would be very important to increase the proportion of such areas [14].

The viability of winter wheat seeds in crop production is determined by a germination test, which includes the test of the germination percentage, germination power and the health of the seedlings [16,17]. Only a healthy and uniformly germinating and growing crop with a strong initial developmental phase can produce a significant quantity and quality of seeds. The quantity and quality of the crop yield and the value of the seed are significantly influenced by the quality of the seed, its physiological properties and the agrotechnological impact during the life of the plant [18]. In seedlings, germination is the final phase of the heterotrophic period of embryonic development, in which the embryo grows out of seed using the reserve nutrients of the endosperm and develops into a seedling subsequently [19]. Fertilization increases the nutrient reserves of the seed [20,21]. An important requirement for good germination is that the seeds and fruits should develop on the mother plant until they are fully grown [22]. Harvesting too late or too early can negatively impact wheat germination [18,23]. Undeveloped, weak seeds have a worse germinating ability, and the plants that develop from them are also poorly developed compared to those harvested at the optimal time. The general ecological requirements for winter wheat germination are moisture, oxygen, pH, light and temperature [24,25]. The seed in the soil needs water to reach a swollen, hydrated state of the tissues and for the enzymes to function [26,27]. The seeds absorb water primarily through the micropyle. Wheat requires a small amount of air. Air intake is initially limited and intensifies when the seed coat bursts open [28]. Under natural conditions, the temperature fluctuates over a wide range, whereas under artificial conditions, the optimal temperature (20–25 °C) for germination can be provided [29]. The development of winter wheat in autumn is determined, on the one hand, by the growing conditions (climatic, soil and agrotechnical factors), and on the other hand, by the characteristics of the seed. The characteristics of the seed can be genetic or acquired during seed production.

Some studies [30,31] failed to confirm the effect of nutrient supply on the germination of winter wheat, while others [32–36] found that nutrient supply had a significant effect on the germination and initial development of winter wheat. Fertilization increases not only the N, P and K content of winter wheat seeds [21], but also the Ca and Mg content [20]. The nutrient content of the seed determines the germination and initial development of the seed [19,34]. The proteins stored in the seed provide the nitrogen that is needed for the seedling for a shorter or longer period of time, and thus, they have a major influence on the initial development of the plant. [19,37]. In winter wheat, an N treatment improves germination and vigour [38], but if too much N is applied, it inhibits germination [39,40] and may reduce the germination percentage [32–34] and seedling vigour [35]. The seed of the best quality is produced with the right proportions of N, P and K treatments determined by the soil conditions [33,34]. Several experiments have found a correlation between seed size and germination parameters [41–47], as well as between seed size, plant development and yield [48–51], whereas some researchers believe that seed size does not influence the development [48] and baking quality of winter wheat [41].

The aim of our research is to examine the effects of different quantities and proportions of nutrients and seed size on the seed testing parameters of winter wheat in a laboratory (germination percentage, germination power, seedling health and vigour) and in the field (emergence percentage), as well as their effects on the yield in the next crop year.

## 2. Materials and Methods

### *2.1. Experiment Background*

The seeds of Hungarian winter wheat cultivar GK Petur from the following four crop years (2005–2006, 2006–2007, 2016–2017 and 2017–2018), and 10 different nutrient levels (control, PK1, PK2, PK3, N1, N2, N3, NPK1, NPK2 and NPK3) were used for seed tests in the long-term (nutrient supply) experiment conducted in Fülöpszállás, Hungary. The weather conditions in Fülöpszállás in the four crop years are shown in Table A1. The driest and warmest year in Fülöpszállás was 2006–2007, and the wettest one was 2017–2018. The lowest mean temperature was in the first study year (2006–2007). The long-term nutrient supply experiment of 40 years in Fülöpszállás was carried out in calcareous meadow soil, which has good N, $P_2O_5$ and $K_2O$ quantities (Table A2). The 10 different nutrient levels in the long-term fertilizing experiment are illustrated in Table 1. The seeds were divided into 3 fractions according to their size: seeds smaller than 2.2 mm, seeds between 2.2 and 2.8 mm and seeds larger than 2.8 mm. The fractional seeds were subjected to germination and vigour tests under laboratory conditions, while germination and yield tests were carried out in the field.

**Table 1.** Nutrient treatment levels of long-term experiment in Fülöpszállás.

| Number of Treatment | Sign of Treatment | N | $P_2O_5$ | $K_2O$ |
|---|---|---|---|---|
| | | kg ha$^{-1}$ Active Ingredient | | |
| 1. | control | 0 | 0 | 0 |
| 2. | PK1 | 0 | 30 | 30 |
| 3. | PK2 | 0 | 60 | 60 |
| 4. | PK3 | 0 | 90 | 90 |
| 5. | N1 | 30 | 0 | 0 |
| 6. | N2 | 60 | 0 | 0 |
| 7. | N3 | 90 | 0 | 0 |
| 8. | NPK1 | 60 | 30 | 30 |
| 9. | NPK2 | 120 | 60 | 60 |
| 10. | NPK3 | 180 | 90 | 90 |

### *2.2. Germination Tests*

Germination tests were carried out under controlled laboratory conditions (20 °C, relative humidity of 80%) with seeds that underwent 10 nutrient treatments (control, PK1, PK2, PK3, N1, N2, N3, NPK1, NPK2 and NPK3) produced in Fülöpszállás and 3 different fraction sizes (smaller than 2.2 mm, between 2.2–2.8 mm and larger than 2.8 mm). The germination test was carried out according to standard protocols established by National Food Chain Safety Office, Hungary (NÉBIH) [52] International Seed Testing Association (ISTA) [53] and MSZ 6354-9: 2016 Seed test methods [54]. In the germination test, 100 seeds were germinated in rolls of germination filter paper, and the test were replicated four times. During the experiment, the germination percentage, germination power and seedling health of each seed lot were determined as follows:

- Germination percentage: Number of seedlings germinated on the 8th day of germination for a given lot of germination (100 seeds) [52–54]. Germination percentage (%) = germinated seedlings on 8th day of germination.
- Germination power: Percentage of the total seedlings (number of seedlings on 8th day of germination) germinated on the 4th day of germination [52–54]. Germination power (%) = number of germinated seedlings on the 4th day of germination × 100/number of germinated seedlings on the 8th day of germination.
- Determination of the health of the seedling: Intact, healthy seedlings (containing at least three strong roots and intact shoot buds) and abnormal or diseased seedlings were separated from each other on the 8th day of germination [52,53]. Seedling health means that a certain percentage of the total seedlings germinated on the 8th day of germination are intact, healthy seedlings [54]. Seedling health (%) = number of healthy, intact seedlings on the 8th day of germination × 100/total number of germinated seedlings on the 8th day of germination.

### *2.3. Vigour Tests*

In the long-term experiment in Fülöpszállás (control, PK1, PK2, PK3, N1, N2, N3, NPK1, NPK2 and NPK3), seeds that underwent 10 nutrient treatments and of 3 different fraction sizes (smaller than 2.2 mm, between 2.2–2.8 mm and larger than 2.8 mm) were used for the vigour tests. The vigour tests were carried out on the winter wheat variety GK Petur using the Szirtes and Barla-Szabó method [55]. For the experiment, 400 seeds were counted and placed in a beaker of 300 mL containing 250 mL of deionised water. The beakers were kept at 20 °C for 48 h, and after two days, fresh water was poured into the beakers, and then they were kept at 5 °C for another 48 h. After a total of 96 h of soaking, the seeds were drained and placed on filter papers for germination. Out of the 400 seeds, 100–100 pieces were placed on a piece of filter paper, respectively, to repeat the experiment four times. An important requirement of seed placement was that the embryo was faced downwards. The seeds were germinated in the rolls of filter paper prepared at 20 °C and at relative humidity of 80%, as described herein. The paper rolls were opened on the 8th day of germination, and the non-germinated seeds and seedlings were separated. The germination vigour value for the given lot (100 seeds) was determined by the number of seedlings (percentages) germinated on the 8th day of germination. Vigour value (%) = germinated seedlings on 8th day of vigour test.

Seedlings were divided into three groups according to the length of the coleoptile:

1. Seedlings of weak vigour: plant with the shortest (about 0.5–2 cm) shoot length.
2. Seedlings of medium vigour: individuals with a shoot length of about 2–4 cm.
3. Seedlings of strong vigour: their shoots were longer than 4 cm.

### *2.4. Field Investigations*

The seeds (at 10 different nutrient levels) produced in Fülöpszállás and fractioned in the laboratory were sown in Szeged as follows: the seeds of the crop year 2005–2006 were sown in October 2006, the seeds of the crop year 2006–2007 were sown in October 2007 and seeds of the crop year 2017–2018 were sown in October 2018. The weather conditions of the three growing seasons in Szeged are shown in Table A3. The driest and warmest year in Szeged was 2006–2007, and the wettest one was 2007–2008. In Szeged, the mean temperature of each year of the study was higher than the long-term average. In Szeged, the field experiment was carried out in deep saline meadow chernozem soil, which has medium N and good $P_2O_5$ and $K_2O$ quantities (Table A2). The GK Petur winter wheat variety was sown in plots of 10 $m^2$ in a random block layout at a seed density of 550 seeds per $m^2$. The experimental plots were treated with the same plant protection and agrotechnological methods.

Seed emergence percentage: The ratio of the number of seeds emerged over the total number of seeds sown. Seed emergence percentage (%) = number of seedlings per 1 $m^2$ in the 3rd week after sowing $\times$ 100/550 (number seed per 1 $m^2$)

Determination of yield: In all three field experimental years, the crops were harvested at the beginning of July using a Wintersteiger plot combine, and then the yield per hectare corrected for a moisture content of 14% was determined.

### *2.5. Statistical Analysis*

Our laboratory tests were carried out for 4 years, and our field tests were carried out for 3 crop years. In both studies, the effects of 3 factors were examined: nutrient supply, seed size and crop year. Statistical analyses were performed by the method of 3-factor variance analysis using the SPSS 27 program [56].

## 3. Results

### *3.1. Laboratory Experiments*

#### 3.1.1. Variance Analysis of Germination Parameters

Table 2 shows the three-factor variance analysis of the germination parameters (with mean square values) performed in the laboratory. Nutrient supply, seed size, crop year and their combination had a significant effect on the germination percentage, germination power, seedling health and vigour value at the 0.001 level. However, the relationship between the nutrient supply and seed size was not significant for germination power.

**Table 2.** Results of variance analysis of germination parameters (MS: mean square values).

| Treatment Number | df | Germination Percentage (MS) | Germination Power of Seeds (MS) | Seedling Health (MS) | Vigour Value (MS) |
|---|---|---|---|---|---|
| Repeat | 3 | | | | |
| Corrected model | 119 | 118.555 *** | 431.979 *** | 109.102 *** | 455.750 *** |
| Intercept | 1 | 4,180,213.408 *** | 2,543,597.066 *** | 4,250,173.297 *** | 3,554,725.519 *** |
| Nutrient treatment | 9 | 278.876 *** | 849.086 *** | 278.051 *** | 2357.065 *** |
| Seed size | 2 | 1948.758 *** | 3630.813 *** | 128.193 *** | 2949.456 *** |
| Crop year | 3 | 488.425 *** | 4876.277 *** | 1623.546 *** | 107.252 *** |
| Nutrient treatment × Seed size | 18 | 33.476 *** | 95.140 $^{ns}$ | 9.402 *** | 326.114 *** |
| Nutrient treatment × Crop year | 27 | 79.214 *** | 409.181 *** | 151.386 *** | 196.156 *** |
| Seed size × Crop year | 6 | 426.417 *** | 378.573 *** | 17.666 *** | 846.290 *** |
| Nutrient treatment × Seed size × Crop year | 54 | 17.326 *** | 126.692 *** | 18.352 *** | 195.481 *** |
| Error | 357 | 8.890 | 61.243 | 1.665 | 10.437 |
| Total | 480 | | | | |

*** Significant at the 0.001 probability level. ns: Non-significant.

#### 3.1.2. Germination Percentage

Figure 1 shows the effects of the nutrient treatments, seed size and crop year for the germination percentage.

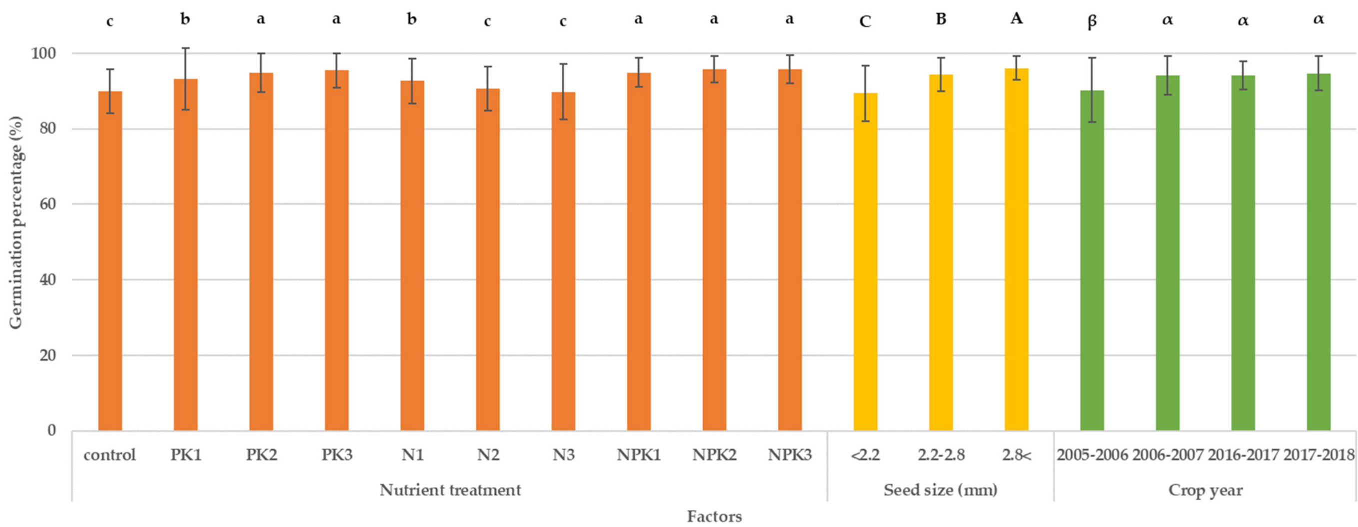


**Figure 1.** Effect of nutrient treatments, seed size and crop year on germination percentage of winter wheat. (Values marked with different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–c) represent nutrient treatments, capital letters (A–C) represent seed sizes and Greek letters (α, β) represent years, where the order of the letters starts from the largest value. The standard deviation (SD) has been marked in the columns.)

According to our results, increasing the doses of the nitrogen treatments (N1, N2 and N3) resulted in a decrease in the rate of germination, so the germination percentage of GK Petur winter wheat variety was more statistically similar at an N dose of between 60 kg ha$^{-1}$ and 90 kg ha$^{-1}$ (89.85–92.73%) compared to that of the untreated control group (98.98%). However, increasing the doses of phosphorus and potassium treatments without nitrogen (PK1, PK2 and PK3) resulted in a higher germination percentage (93.17–95.46%), and all of the PK treatments had a significantly higher germination percentage compared to those of the untreated control (Figure 1). Increasing the doses of the 2:1:1 NPK treatments (NPK1, NPK2 and NPK3) increased the germination percentage, and they all showed a significantly higher germination percentage than those of the untreated control group and the group that underwent the nitrogen treatments (N1, N2 and N3).

The smallest germination percentage was observed for the smallest (>2.2 mm) seeds (89.40%), the largest germination percentage was found for the largest (<2.8 mm) seeds (96.09%) and the germination percentages of all three seed size fractions differed significantly from each other.

The highest germination percentage was observed in the first experimental crop year (95%). Significantly lower values were found in the other three crop years (94.09–94.66%).

#### 3.1.3. Germination Power of Seeds

Figure 2 shows the effects of the nutrient treatments, seed size and crop year on the germination power of seeds of winter wheat.

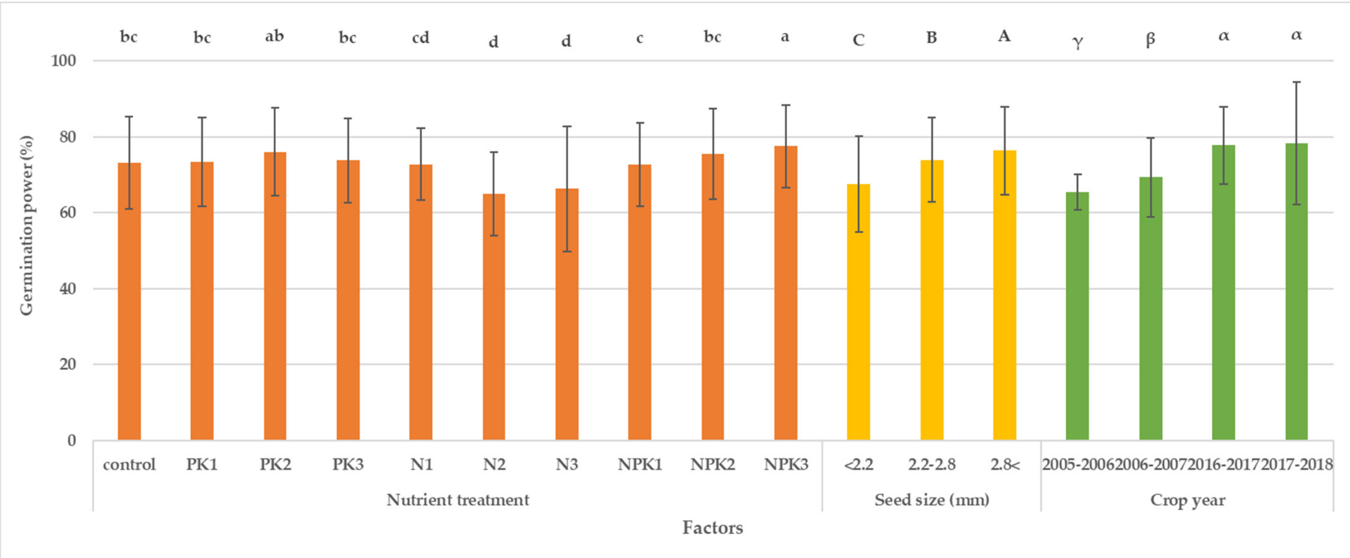


**Figure 2.** Effect of nutrient treatments, seed size and crop year on germination power of winter wheat. (Values marked with different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–d) represent nutrient treatments, capital letters (A–C) represent seed sizes and Greek letters (α–γ) represent years, where the order of the letters starts from the largest value. The standard deviation (SD) has been marked in the columns.)

The slowest seed germination was observed in the treatments with pure nitrogen (N1, N2 and N3) (germination power: 65.02–72.80%). The seeds that underwent the treatments with between 60 kg ha$^{-1}$ and 90 kg ha$^{-1}$ N had a significantly lower germination power than the seeds that underwent the other treatments did. Although the PK treatments without nitrogen (PK1, PK2 and PK3) had a higher germination power (73.38–76.08%) than the seeds of the untreated control plot did (73.13%), a significant difference was not detected between them. Increasing the doses of the 2:1:1 NPK treatments resulted in a higher germination percentage. Among all of the nutrient treatments, the seeds treated with N 180 kg ha$^{-1}$, P 90 kg ha$^{-1}$ and K 90 kg ha$^{-1}$ germinated the most dynamically, which is confirmed by the fact that 77.54% of all of the germinated seeds germinated on the 4th day.

As the seed size increased, germination became more dynamic: the smallest seeds (>2.2 mm) had the lowest germination power (67.54%), the largest seeds (<2.8 mm) had the highest germination power (76.36%) and all three seed size fractions had significantly different germination powers.

Figure 2 shows the effects of the four experimental years on the germination power. It can be seen that the seedlings of the last two years germinated at a higher rate (77.80% and 78.24%, respectively). The germination power of the seeds of the second year (2006–2007) was significantly lower (69.40%) compared to those of the last two years, and the first year produced the weakest germination power (65.48%) out of all of them.

#### 3.1.4. Seedling Health

Figure 3 shows the effects of nutrient treatments, seed size and crop year on the seedling health of winter wheat.

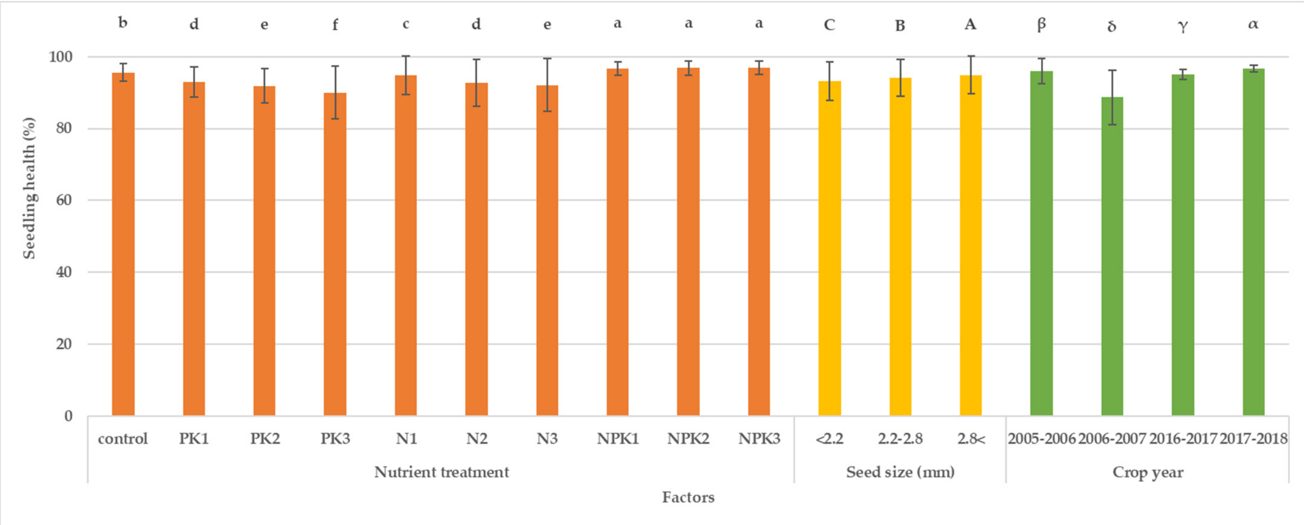


**Figure 3.** Effect of nutrient treatments, seed size and crop year on seedling health of winter wheat. (Values marked with different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–f) represent nutrient treatments, capital letters (A–C) represent seed sizes and Greek letters (α–δ) represent years, where the order of the letters starts from the largest value. The standard deviation (SD) has been marked in the columns.)

The seedlings from both the unilateral N and PK treatments without N were in a poorer health state, with a higher rate of abnormal seedlings than that of seedlings from the control plots (95.60%). There were significant differences between the seedlings in the control plots and plots of N treatments, which is similar to the control plots and the plots of PK treatments. Increasing the dose of the pure N and PK treatments significantly increased the proportion of abnormal seedlings. It can be observed that the health of the seedlings improves with increasing the dose of 2:1:1 treatment (NPK1, NPK2 and NPK3), but there are no major differences between them. The seeds that underwent the 2:1:1 treatment were found to be statistically healthier (96.69–96.92%) than the seedlings developed from the seeds that underwent all of the other treatments.

The bigger seed size results in healthier seedlings, and all three seed size fractions were significantly different.

The highest percentage of abnormal seedlings was observed in the second year of the experiment (88.92%). The healthiest seeds were developed in the crop year 2017–2018 (96.72%). The health of the seedlings differed significantly in each experimental year, and the condition of the seedlings improved according to the total amount of precipitation in the crop years.

#### 3.1.5. Vigour Value of Seed

Figure 4 shows the effects of the nutrient treatments, seed size and crop year on the vigour value of the seed of winter wheat. Three categories of weak, medium and strong vigour values (%) were created based on the shoot length of the seedling.

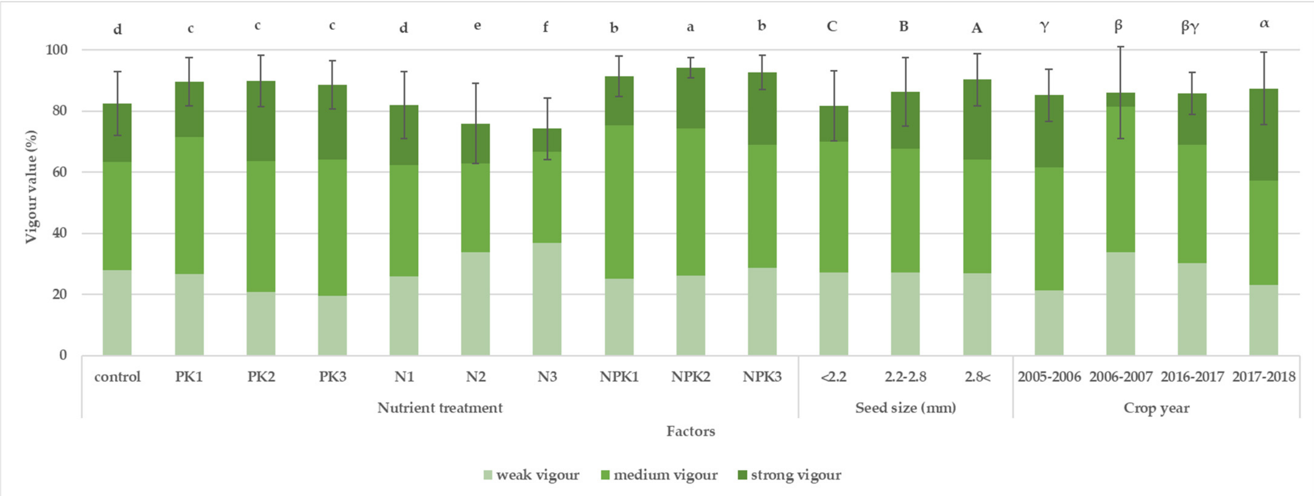


**Figure 4.** Effect of nutrient treatments, seed size and crop year on vigour value of winter wheat. (Values marked with different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–f) represent nutrient treatments, capital letters (A–C) represent seed sizes and Greek letters ($\alpha$–$\gamma$) represent years, where the order of the letters starts from the largest value. The standard deviation (SD) has been marked in the columns.)

Increasing the N dose in the nutrient treatment gradually reduced the vigour value, thus the seeds with the highest N dose (90 kg ha$^{-1}$) had the lowest vigour value (74.25%). Increasing the dose of the unilateral N treatments reduced the number of seedlings with more vigour, while at the same time, the number of seedlings with less vigour also increased. The PK treatments without N resulted in seedlings with significantly higher vigour values compared to those of the untreated control. Increasing the PK doses in the treatment reduced the number of seedlings with less vigour. The 2:1:1 ratio of treatments (NPK1, NPK2 and NPK3) showed remarkably higher vigour values (91.38–94.15%) compared to those of other treatments. By increasing the dose of the 2:1:1 NPK treatments, the proportion of seedlings with more and less vigour also increased, while the proportion of seedlings with medium vigour values decreased.

Seeds of bigger sizes had significantly higher vigour values (90.26%). In the faction of seeds of bigger sizes, the rate of seedlings with more vigour increased, while the rate of seedlings with medium and low vigour values decreased.

The lowest vigour value was obtained in the first year of the experiment (85.12%), and the highest vigour value was obtained in the last year of the study (87.37%). There was a significant difference between these two years and between the vigour values of the 2016–2017 and the 2017–2018 crop years. Seeds grown in the driest crop year had the highest proportion of seedlings with less vigour and the smallest proportion of strong seedlings, whereas in the rainy crop year between 2017 and 2018, the highest proportion of strong seedlings was found.

### 3.2. Field Investigations

#### 3.2.1. Variance Analysis of Field Investigations

Table 3 shows the results of the three-factor variance analysis (with mean square values) of the field tests conducted in Szeged. The nutrient supply, seed size, crop year and their combination influenced the emergence percentage of the wheat crop in the following year at a 0.001 level. Seed size and crop year at the 0.001 level, nutrient supply at the 0.01 level and seed size × crop year at the 0.05 level significantly affected the yield in the next crop year. The variance analysis shows that the relationships between nutrient supply × seed size, nutrient supply × crop year and nutrient supply × seed size × crop year were not significant for the yield of the next crop year.

**Table 3.** Results of variance analysis of field investigations (MS: mean square values).

| Number of Treatment | df | Emergence Percentage (MS) | Yield (MS) |
|---|---|---|---|
| Repeat | 3 | | |
| Corrected model | 89 | 199.415 *** | 0.699 *** |
| Intercept | 1 | 2,885,727.380 *** | 12,657.822 *** |
| Nutrient treatment | 9 | 824.765 *** | 0.722 ** |
| Seed size | 2 | 2140.950 *** | 15.000 *** |
| Crop year | 2 | 185.663 *** | 4.869 *** |
| Nutrient treatment × Seed size | 18 | 109.866 *** | 0.135 ns |
| Nutrient treatment × Crop year | 18 | 43.565 *** | 0.309 ns |
| Seed size × Crop year | 4 | 213.485 *** | 0.712 * |
| Nutrient treatment × Seed size × Crop year | 36 | 57.115 *** | 0.142 ns |
| Error | 267 | 7.309 | 0.273 |
| Total | 360 | | |

*** Significant at the 0.001 probability level. ** Significant at the 0.01 probability level. * Significant at the 0.05 probability level. ns: Non-significant.

### 3.2.2. Emergence Percentage in Field

Figure 5 shows the effects of the nutrient treatments, seed size and crop year on the emergence percentage of winter wheat.

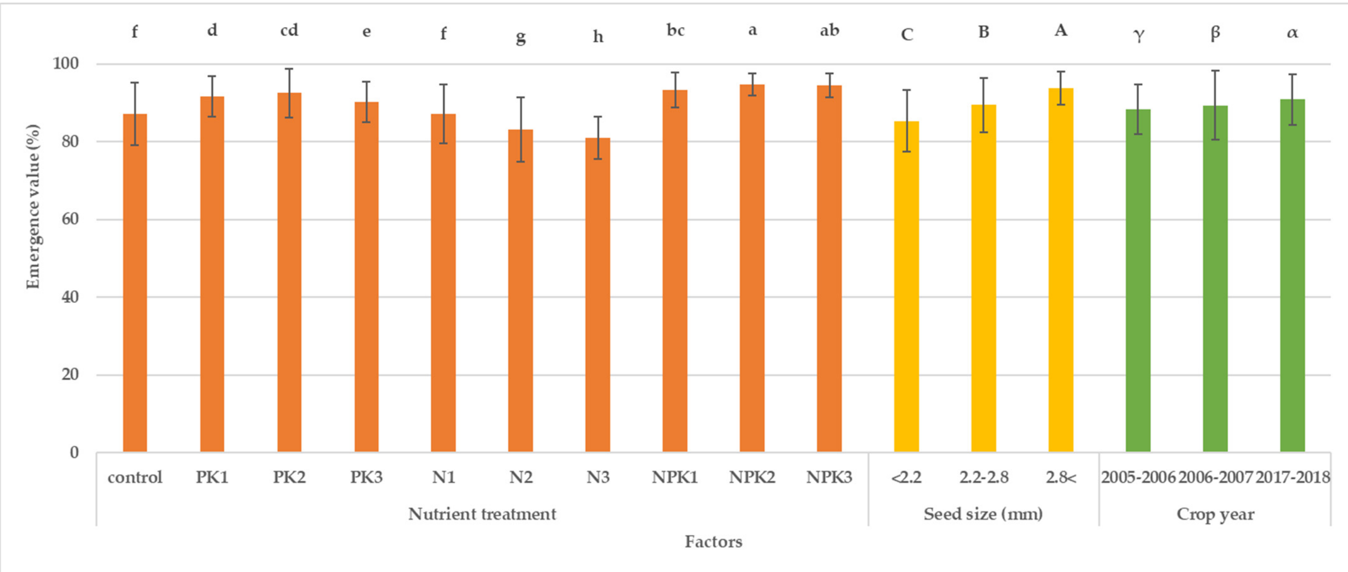


**Figure 5.** Effect of nutrient treatments, seed size and crop year on emergence percentage of winter wheat. (Values marked with different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–h) represent nutrient treatments, capital letters (A–C) represent seed sizes and Greek letters (α–γ) represent years, where the order of the letters starts from the largest value. The standard deviation (SD) has been marked in the columns.)

The seeds that underwent the unilateral N treatments germinated worse than the seeds in the untreated control group did (87.20%). It can be observed that higher N doses resulted in a lower emergence percentage of the next generation. There were significant differences in the emergence percentage between the control plots and the plots treated with N of 60 kg ha$^{-1}$ and between the control plots and the plots treated with N of 90 kg ha$^{-1}$. The PK treatments significantly increased the emergence percentage of the next generation of winter wheat (90.26–92.48%) compared to that of the control (87.20%). The highest emergence percentages were recorded for the 2:1:1 NPK treatments (93.36–94.74%). A similar correlation was observed in the PK and NPK treatments with increased doses: as the nutrient dose increased, the emergence percentage also increased, but overly high doses of nutrients decreased the emergence percentage of winter wheat in the next generation.

The increase in the seed size of winter wheat improved the emergence percentage, with significant differences in all three seed size fractions.

The emergence percentage showed a significant difference in the 3 years of the study: the years of 2005 and 2006 showed the lowest values, and the years of 2017 and 2018 produced the highest number of seedlings.

### 3.2.3. The Yield of Winter Wheat in the Next Generation

Figure 6 shows the effects of nutrient treatments, seed size and crop years on the yield of winter wheat.

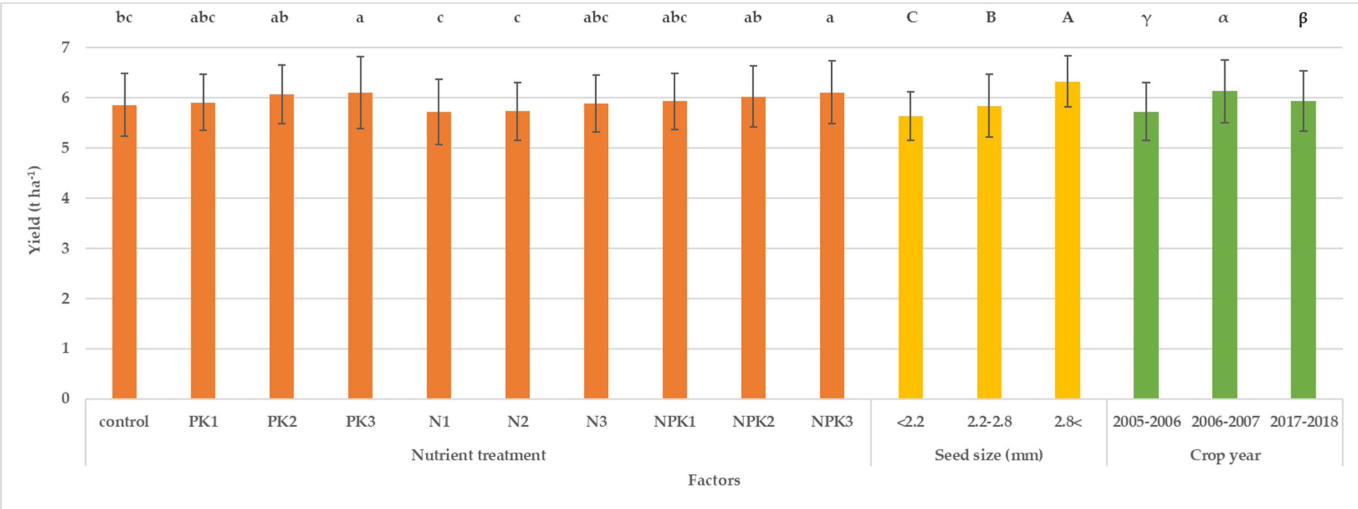


**Figure 6.** Effect of nutrient treatments, seed size and crop year on yield of winter wheat. (Values marked with different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–c) represent nutrient treatments, capital letters (A–C) represent seed sizes and Greek letters (α–γ) represent years, where the order of the letters starts from the largest value. The standard deviation (SD) has been marked in the columns.)

Seeds from the unilateral N treatments had similar or rather lower yields (5.72–5.88 t ha$^{-1}$) in the next crop year than those of the seeds from untreated control plots (5.86 t ha$^{-1}$). In contrast, the next generation of seeds that underwent all of the PK treatments produced higher yields (5.90–6.10 t ha$^{-1}$) compared to those of the control plots. In addition, by increasing the dose of PK, the differences in yields increased more in the next generation compared to those of the controls, thus a significant difference was found between the seeds treated with the highest PK dose (90 kg ha$^{-1}$) and the seeds in the control group. The effects of the NPK treatments at a 2:1:1 ratio on the yield (5.92–6.10 t ha$^{-1}$) in next year was greater and more significant than those of the control treatment, and this increased by increasing the dose of the nutrient. The seeds grown on the plots treated with the highest dose of NPK (180 + 90 + 90 kg ha$^{-1}$ NPK) in Fülöpszállás produced a significantly higher yield in the next year in Szeged than the seeds of the control plots did.

On average, over the 3 years of the study, the yields in the following crop years increased significantly as the seed size increased.

The lowest yield was produced in the first year of the study (5.72 t ha$^{-1}$), and the highest yield was produced in the second crop year (6.13 t ha$^{-1}$). Although there were significant differences between the yields in the different crop years, these were not related to the amount of precipitation in the year of seed production, but rather, the results show a correlation with the amount of precipitation in the growing season in Szeged.

## 4. Discussion

High-quality yields are the results of favorable interaction of many factors. One of these factors, and perhaps the most important one, is the seed or the biological basis [46]. A certificated or controlled seed in itself is a guarantee of a good harvest. In this sense, a high-quality seed is and will continue to be one of the most important factors in applied agrotechnology. At the same time, the primary issue for farmers is the price of the seed, not its quality. For this reason, it is typical that farmers often use their own seeds in the following crop year [14]. Our study highlights that the quality of the seed, the amount of nutrient supply, the seed size and the weather in the crop year substantially influence the different seed test parameters of winter wheat in the laboratory and in the field.

In order to maintain a good germination rate of the winter wheat, an adequate N supply must be provided during the seed filling period [38], however, excessive N application can cause germination inhibition [39]. Our study confirmed this finding as the increase in the dose of N in both the laboratory and field conditions decreased the germination rate. Our results show that unilateral N treatments reduce the germination power of winter wheat compared to that of controls without additional nutrients. Germination occurred significantly slower for the seeds that underwent the unilateral seed treatments of 60 kg ha$^{-1}$ and 90 kg ha$^{-1}$ N, respectively. One-sided N treatments resulted in insufficient and inadequate plant nutrition and significantly impaired seedling health, which deteriorated as the N dose increased. As a result of such treatments, more abnormal seedlings grow, which develop poorly or die. Our statistical analysis proved that increasing the N dose decreased the vigour value of winter wheat, however, other authors found the opposite [38], claiming that the vigour of winter wheat seed improved by increasing the N dose.

Our findings show that PK treatments without N results in significant increases in the germination percentage (which increases with an increasing dose), in seed vigour and in the field emergence percentage. In other words, an adequate PK supply during seed production is essential for ideal germination and initial development. The supply of phosphorus and potassium improves the germination power and germination percentage of the seed [32–34], as well as the vitality and vigour of the seedlings [35], the formation of shoots and the initial growth of winter wheat [36]. The initial developmental advantage of plants can be maintained at later developmental stages, and they can avoid the negative impacts more easily. However, we have also found that the PK treatment without N deteriorates the health of the seedlings rapidly, which increases by increasing the PK dose. A one-sided plant nutrition supply had a long-term negative effect on the development of the next generation of the plant through the seed. As a result of the 2:1:1 complete NPK treatments, all of the tested parameters (germination percentage, germination power, seedling health, vigour, emergence percentage and yield of next crop year) improved more compared to those of the control group. The germination power, the seedling health and the yield of the next generation of the plant increased by increasing the NPK dose. It should also be noted that an excessive increase in the amount of nutrients, regardless of the needs of the plant and the condition of the soil, does not ensure a good harvest. All of the seed parameters improved at doses of 120 kg ha$^{-1}$ nitrogen, 60 kg ha$^{-1}$ phosphorus and 60 kg ha$^{-1}$ potassium, but the germination percentage, vigour value and emergence percentage also deteriorated with the largest nutrient doses (180 kg ha$^{-1}$ nitrogen, 90 kg ha$^{-1}$ phosphorus and 90 kg ha$^{-1}$ potassium). Based on our findings, it can be concluded that the correct proportion of nutrients is a much more important variable than the amount of fertilizer that is applied.

Healthy, fast and evenly developing seedlings are more resistant to the effects of the weather. A uniform seed size is an essential factor to achieve evenly developing seedlings. There is a correlation between seed size and seedling development. In our study, a bigger seed size significantly increased the germination percentage, which confirmed the findings of some authors [42,44–46,57], while it refuted other findings [58]. Our results show that increasing the seed size significantly improves vigour, which reflects the opinion of several other authors [40,46]. Our findings confirmed that a bigger seed size significantly increased the health of the seedlings, the emergence of plants [41–43], plant development [46,47,57] and the yield [48–50,58]. However, some study claim that a bigger seed size of winter wheat does not produce higher yields [51,59] or improve the baking quality [41]. Our test results support [51] the view that smaller seeds should be removed from the seed lot, as they will only deteriorate the properties of the seed lot.

The impact of the weather on the crops during a specific year has not been entirely proven. A systematic and significant correlation was found between the health or the shoot length of the seedlings and the amount of precipitation during the crop year of seed production. Weather conditions are most likely to influence seed quality parameters in seed production and the initial development of the seedling. In addition, these effects and their consequences do not persist until the next generation of crop production. The weather in the crop year has a greater impact on yield than the weather in the year of seed production does. Our results raise additional questions that require a deeper analysis of the data.

However, it should be noted that seeds of the same variety and the same physical parameters may react differently to diverse meteorological events. Extreme weather events also occur in this country. We cannot prevent their negative effects; extreme weather events significantly test the resilience and adaptability of cultivated plants. During the initial developmental phase of winter wheat, a gradual increase in temperature and the uneven distribution of precipitation may cause damage to the plants. Therefore, it is extremely important that the wheat stock base consists of seeds that are able to develop optimally in the year of seed production. Based on the results of our investigation, it can be concluded that the effects (weather and nutrient supply) on the mother plants mainly influence the initial development of the plant, i.e., the germination parameters. The yield of the next plant generation is mainly determined by the weather during the year. We can also note that difficulties in the initial developmental phase of winter wheat can also affect the later stages of its development, and this is reflected in the yield. Due to changing environmental conditions, the use of high-quality, uniform seeds, as well as the provision of adequate nutrient supply, are valued more highly [60,61]. This conclusion draws attention to the fact that these findings not only determine the harvest time of the specific year, but they also have significant impacts on the yield and initial development of the plant in the following year, which provides a good starting point for the development of the yield. Of course, when one is choosing the optimal amount of nutrients and their proportion on a specific production site, it is essential to know the agroecological properties, soil conditions and crops produced in the plot the year before the needs of the plants that are to be grown, which is the responsibility of the producer.

In natural field conditions, environmental factors (temperature, precipitation supply, air content of the soil, etc.) vary over a wide range, but seed tests in artificial conditions are carried out under optimal conditions [29]. Thus, germination laboratory tests are less realistic models of the field conditions, however, some stress effects reflecting field difficulties can be studied in vigour tests [30,62]. In any case, it should be emphasised that seed tests need to be repeated under non-optimal germination conditions [63,64] in order to determine the true value of the seeds.

## 5. Conclusions

Uniform and complete plant emergence in autumn is a key factor of wheat production, since it has a major impact on the yields. The impacts of stress at the time of plant emergence can be reduced by using certified seeds (fractionated by size) and seeds with good biological properties, as well as by using appropriate agrotechnology. Based on our results, the following conclusions can be drawn:

- Compared to the untreated controls, the unilateral nitrogen treatments significantly reduced the health of the seedling of the next generation. The germination percentage, seedlings health, vigour value and emergence percentage decreased with the increase in the N dose.

- Phosphorus–potassium treatments significantly increased the germination percentage, vigour value and field emergence percentage and significantly reduced the health of seedlings compared to that of the untreated controls. Increasing the phosphorus and potassium dose increased germination percentage and the yield of the next generation of the plant and decreased the health of the seedlings.
- The 2:1:1 ratio NPK treatments improved all of the t-tested parameters (germination percentage, germination power, seedling health, vigour value, field emergence percentage and yield of next crop year) compared to those of the controls. Increasing the NPK dose increased the germination power, the health of the seedling and the yield of the next generation of the plant.
- The increase in seed size significantly increased germination percentage, germination power, seedling health, vigour value, emergence percentage and the yield in the following crop year.
- The correlation between the weather components of the year of seed production and seed quality was not significant and conclusive. Although there was a trend and significant difference in the seedling health and the shoot length of the seedlings, the other tested parameters (germination percentage, germination power, vigour value, emergence percentage and yield of the next crop year) showed no correlation with the crop year.

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## Appendix A

**Table A1.** Monthly precipitation and temperature in the 4 crop years in Fülöpszállás.

| | Precipitation (mm) | | | | | Temperature (°C) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Month** | **2005–2006** | **2006–2007** | **2016–2017** | **2017–2018** | **40 Year Average** | **2005–2006** | **2006–2007** | **2016–2017** | **2017–2018** | **30 Year Average** |
| October | 4.70 | 23.50 | 80.60 | 77.40 | 40.63 | 9.80 | 10.50 | 14.10 | 13.00 | 12.18 |
| November | 29.40 | 12.80 | 52.00 | 33.40 | 44.19 | 4.00 | 6.00 | 7.70 | 9.70 | 5.95 |
| December | 47.00 | 0.00 | 0.00 | 48.00 | 34.88 | 0.10 | 4.00 | 1.30 | 3.70 | 3.98 |
| January | 27.70 | 15.80 | 50.60 | 44.50 | 30.45 | −4.50 | 4.50 | −0.70 | −0.60 | 1.45 |
| February | 34.50 | 45.70 | 48.80 | 79.70 | 30.05 | 1.00 | 5.10 | 4.10 | 5.70 | 2.28 |
| March | 40.40 | 27.40 | 38.10 | 82.60 | 30.05 | 6.00 | 6.50 | 9.30 | 7.30 | 8.50 |
| April | 45.80 | 2.50 | 31.50 | 33.10 | 35.40 | 13.00 | 12.50 | 13.30 | 12.40 | 11.90 |
| May | 40.50 | 77.50 | 127.10 | 111.80 | 64.97 | 16.00 | 19.00 | 14.90 | 15.60 | 15.47 |
| June | 107.40 | 81.90 | 64.20 | 147.90 | 66.59 | 15.00 | 22.00 | 21.10 | 20.30 | 21.23 |
| July | 81.40 | 22.10 | 60.50 | 50.00 | 62.90 | 23.50 | 22.00 | 22.00 | 21.80 | 23.18 |

**Table A2.** Soil characteristic of experimental sites.

| | Fülöpszállás | Szeged |
|---|---|---|
| pH (KCl) | 7.57 | 7.34 |
| Ca (m m%$^{-1}$) | 7.85 | 1.88 |
| $CaCO_3$ (m m%$^{-1}$) | 19.6 | 4.7 |
| Humus (m m%$^{-1}$) | 3.03 | 2.94 |
| $NO_3$-$N^+$ $NO_2$-$N^+$ (mg kg$^{-1}$) | 14.2 | 24 |
| $P_2O_5$ (mg kg$^{-1}$) | 172 | 248 |
| $K_2O$ (mg kg$^{1}$) | 384 | 209 |
| Mg (mg kg$^{-1}$) | 495 | 167 |
| Na (mg kg$^{-1}$) | >300 | 84 |
| Zn (mg kg$^{-1}$) | 0.9 | 0.9 |
| Cu (mg kg$^{-1}$) | 2.4 | 1.8 |
| Mn (mg kg$^{-1}$) | 18 | 22 |
| All salt (m m%$^{-1}$) | 0.029 | 0.044 |
| $SO_4$-S (mg kg$^{-1}$) | 22.6 | 9.7 |
| Fe (mg kg$^{-1}$) | 14 | 14 |

**Table A3.** Monthly precipitation and temperature in the 3 crop years in Szeged.

| | Precipitation (mm) | | | | Temperature (°C) | | | |
|---|---|---|---|---|---|---|---|---|
| **Month** | **2006–2007** | **2007–2008** | **2018–2019** | **40 Year Average** | **2006–2007** | **2007–2008** | **2018–2019** | **30 Year Average** |
| October | 21.00 | 67.20 | 4.70 | 47.75 | 11.00 | 10.50 | 12.30 | 11.63 |
| November | 24.20 | 59.40 | 21.30 | 32.64 | 7.00 | 7.50 | 8.90 | 2.06 |
| December | 2.00 | 49.30 | 28.10 | 30.02 | 3.00 | 1.50 | 1.70 | 1.69 |
| January | 32.40 | 7.80 | 19.50 | 33.42 | 4.50 | −3.00 | −0.20 | 0.38 |
| February | 29.40 | 2.10 | 13.40 | 39.34 | 5.50 | 3.00 | 4.60 | 2.06 |
| March | 56.00 | 62.60 | 1.70 | 34.36 | 8.00 | 8.00 | 9.60 | 7.13 |
| April | 3.20 | 39.70 | 55.70 | 32.71 | 13.00 | 12.00 | 13.50 | 12.00 |
| May | 106.90 | 60.50 | 136.50 | 86.59 | 15.00 | 16.00 | 15.50 | 16.00 |
| June | 35.70 | 117.90 | 134.70 | 77.53 | 22.00 | 19.00 | 22.10 | 21.10 |
| July | 17.20 | 55.00 | 26.00 | 61.90 | 24.00 | 23.00 | 22.50 | 22.71 |

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