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# Effect of the pre-magnetic treatment of seeds and the N-fertilizer on the yield and quality of groundnut grown in sandy soil

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**ABSTRACT**

This field trial aimed to study the effect of the magnetic treatment (MT) of urea as a nitrogen (N) fertilizer as well as the MT of the groundnut (*Arachis hypogaea* L.) seeds before sowing on the crop yield and quality under sandy soil conditions during the summer seasons of 2020 and/or 2021. Treatments were distributed in a split-plots design in triplicates. The control CL has received the recommended dose RD of the N-fertilizer while other treatments received the rates 50, 75, and 100% of the RD as magnetized urea (main factor F1) applied to the surface soil. The sub-factor (F2) was the time of MT (15, 30, and 45 min) of the groundnut seeds exposed to magnetic field MF 1.4 T before planting. Representative samples from the soil and plant were taken after harvesting. At the 15-min time and 100% N-fertilization, the yield of pods and seeds (kg $ha^{-1}$) has increased relatively by 8.2% and 9.7% respectively, compared to the corresponding CL. At the 30-min time and 50% and 100% N-fertilization, the yield (kg $ha^{-1}$) has increased relatively by 9.7% and 13.3% respectively for pods and by 10.1% and 16.8% respectively for the seeds. At the 45-min time and 50% N-fertilization, the yield (kg $ha^{-1}$) has increased by 12.4% and 14.6% for pods and seeds, respectively. The 100% N-fertilization along with 15 min MT before cultivation or the 50% and/or 100% N-fertilization along with 30 min MT or the 50% along with 45 min MT could be recommended. The agronomic efficiency (AE) for the N, P, and K nutrients was increased by the MT in the order 15 min < 30 min < 45 min at the 50, 75, and 100% N-fertilization rates.

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## 1. INTRODUCTION

Agronomic studies targeting to minimize the different doses of the applied fertilization are continuous for economic, environmental, and health aspects. Sandy soils are often reclaimed soils that need a continued application of bio-, and/or organic as well as the mineral fertilizers to maintain its nutritional status and crop productivity (El-Serafy & El-Sheshtawy, 2020; Helaly et al., 2020; Leggo, 2014).

The technology of magnetic treatment (MT) is widely applied in agriculture to increase the use efficiency of saline and low quality irrigation water (Abedinpour & Rohani, 2016), activate seeds before cultivation (Harb et al., 2021) or even to enhance the effect of the applied fertilizers (Kamali et al., 2021; Mohamed, 2020; Vasilyeva et al., 2021). The exposure to a magnetic field (MF) induces the constituents of the matter resulting in many changes that are sometimes temporary. The magnetic induction does not change the atomic/molecular constitution of a matter but may affect its' polarization or dipole moment. The exposure of water and some solvents to a MF influences the macroscopic and microscopic properties including the molecular and atomic structures and the electronic motions. This was indicated by the splitting of the spectral peaks of the Infrared, Raman, visible, ultraviolet and X-ray spectra depending on the magnetization time, the MF intensity and the temperature of medium. The intra- and intermolecular hydrogen bonds networks along with the Van der Waal's forces between the molecules forming the water structure when present become weaker that known as the Zeeman Effect. The Infrared peaks has indicated the presence of a H-bonded and non-H-bonded – OH groups. Some physicochemical properties of the magnetized water were affected due to the changed size of water clusters. Increasing the intensity of the applied MF decreases the water surface tension, which affects the capillary rise of water (Karkush et al., 2019). Such treated water may break the large moieties into smaller ones and facilitate passing through the pores of plants and soils. It increases the dissolution of minerals to provide sufficient nutrients for plants. The plant roots can absorb soluble nutrients necessary to grow, and eliminate the non-nutritive salt ions so that the remained salt crystals are easily leached from the soil (Absalan et al., 2021; Karkush et al., 2019).

Seed priming, coating, and pelleting in addition to the thermal treatment are practices for the seed germination enhancement. The pre-sowing MT of seeds was extensively studied for many types of plants such as tomato, onion, wheat, sunflower, etc (Hussain et al., 2020). The accelerated germination percentage, increased root and shoot length, leaf area, improved yield, and yield parameters due to the improved plant nutrition are some beneficial effects obtained for the magnetically treated seeds before cultivation. Some theories were suggested by researchers to define the magnetic stimulation of seeds. It may cause biochemical changes and variations in the enzymes' activities that affect the plant processes like photosynthesis, nutrients uptake, growth, ionic balance, and transportation across the cell membranes, which become more permeable (Harb et al., 2021). A direct exposure of seeds to the MF as well as the hydro priming in a magnetically treated water (MTW) were efficient practices to obtain many advantages of the MT. It keeps the seed quality against the oxidizing agents causing the degradation upon storage that inhibits their germination (Afzal et al., 2021).

On another hand, little studies were defined in the literature about the MT of fertilizers and/or their efficiency for the crop production. The uptake of nutrients was studied in hydroponic systems using a MTW with MF intensities 0.1 and 0.2 Tesla. Solutions of nutrients were magnetized after preparation as well as nutrients were added to the pre-magnetized water. An enhancement was recorded in the uptake of nutrients including the $N^+$, $P^+$, $K^+$, $Ca^{2+}$, $Fe^{2+}$, and $Zn^{2+}$, stimulation in the chlorophyll and carbohydrates content and a biomass accumulation (Zareei et al., 2021).

The magnetic susceptibility ($\chi_m$, $m^3$ $mol^{-1}$) of some chemical elements and compounds may play a role in their response to the MF and their effect upon application. Positive and negative values of susceptibility ($\chi_m$) are expected vital property because of which the behaviour of a substance may change if exposed to a MF. Some values of compounds used as fertilizers are available, for example, the $\chi_m$ for aqueous Ammonia $NH_3$ is – 18.3 $m^3$ $mol^{-1}$, Ammonium nitrate $NH_4NO_3$ – 33 $m^3$ $mol^{-1}$, Ammonium sulfate $(NH4)_2SO_4$ – 67 $m^3$ $mol^{-1}$, white Phosphorus P – 26.66 $m^3$ $mol^{-1}$, Potassium nitrate $KNO_3$ – 33.7 $m^3$ $mol^{-1}$, Potassium sulfate $K_2SO_4$ – 67 $m^3$ $mol^{-1}$. This study aims to indicate the effect of the magnetic treatment MT of the solid-state nitrogen (N) fertilizer and the groundnut (*Arachis hypogaea* L.) seeds before cultivation on the crop yield and the nutrients use efficiency (NUE) under the sandy soil conditions.

## 2. MATERIAL AND METHODS

The field experiment was carried out at the Ismailia Agricultural Research Station, (30° 35' 30" N 32° 14' 50" E elevation 3 m – Ismailia city) Soils, Water and Environment Research Institute/Agricultural Research Center (ARC), Egypt, during the summer seasons (May – October) of the years of 2020 and 2021. Table 1 presents some properties of the experiment sandy soil classified as *Typic Torripsamment; Entisol* [Arenosol AR].

Before planting, a 476.19 kg $ha^{-1}$ RD of the super Calcium phosphate as a P-fertilizer were mixed with the soil, while a 119 kg $ha^{-1}$ of the $K_2SO_4$ (48% $K_2O$) was applied in two equal doses after planting as recommended by the Egyptian Ministry of Agriculture (El-Basioni et al., 2015).

The mineral N-fertilizer was urea 46% N spread on the soil surface without magnetization in a three equal doses 30, 45, and 60 days after planting to obtain the total recommended dose RD as 142.86 N units per hectare for the control (CL) plots. The magnetized urea in the solid form was obtained by placing the required amount in a magnetic field MF of intensity 1.4 Tesla inside a magnetic tube (70 cm Length × 1.5-inch diameter) for 30 min (it is neither a standard time of MT nor recommended, it is only suggested by some researchers as an exposure time). Application rates 50 , 75 , and 100 % of the N (RD) were applied to the surface soil in a three equal doses 30, 45, and 60 days after planting (main factor F1).

The groundnut seeds (*Arachis hypogaea* L., cv. Giza 5) to be used as tested treatments except the control seeds were placed in a MF of intensity 1.4 Tesla inside a magnetic tube (70 cm Length × 1.5-inch diameter) for 15, 30, and 45 min before planting (sub-factor F2). The groundnut seeds were sown in holes (20-cm apart) in lines (50-cm apart) on the 15$^{th}$ of May 2020 and/or 2021. The treatments were distributed in a split-plots design with three replicates and a plot area 10.5 $m^2$ (3.0 m × 3.5 m). The recommended agronomic practices by the Egyptian Ministry of Agriculture for the groundnut cultivation in sandy soil were followed.

Representing samples from the soil and plants after the crop harvesting (October 2020 and 2021 respectively) were selected and air-dried for analysis . The soil pH, EC (dS $m^{-1}$), and the available K, Fe, Mn, and Zn (mg $kg^{-1}$) were estimated as well as the yield (kg $ha^{-1}$) was calculated based on the seed yield per plot area and the mean of the two seasons were obtained. Some yield parameters including the plant height (cm) and weight (g), no. of pods/plant, wt. pods/plant (g), wt. seeds/plant (g) and the 100-seeds weight (g) were also recorded.

**Table 1.** Some characteristics of the experiment soil before cultivation

| | Particle size distribution (%) | | | |
|---|---|---|---|---|
| | Coarse sand | Fine sand | Silt | Clay |
| | 70.12 | 14.32 | 6.22 | 9.34 |
| Texture class | $CaCO_3$ (%) | Organic matter OM (%) | pH† | Electrical conductivity EC (dS $m^{-1}$)‡ |
| Sandy | 0.38 | 0.26 | 7.90 | 0.40 |
| | Available nutrients (mg $kg^{-1}$) | | | |
| | N | P | K | |
| | 25.50 | 2.20 | 55.16 | |

**Remarks**: † (1:2.5 soil: water suspension); ‡ (1:5 soil: water extract)

**Table 2.** Effect of the studied treatments on some of the experimental soil properties

| The applied N-fertilization from the RD | pH (1:2.5) | | | | EC (dS m$^{-1}$) | | | | Available concentration (mg kg$^{-1}$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | N | | | | P | | | | K | | | |
| | CL | Time of MT (min) | | | CL | Time of MT (min) | | | CL | Time of MT (min) | | | CL | Time of MT (min) | | | CL | Time of MT (min) | | |
| | | 15 | 30 | 45 | | 15 | 30 | 45 | | 15 | 30 | 45 | | 15 | 30 | 45 | | 15 | 30 | 45 |
| 50% | 7.99 | 7.97 | 7.95 | 7.92 | 1.09 | 1.07 | 1.04 | 1.01 | 37.40 | 39.74 | 43.87 | 47.50 | 4.02 | 4.75 | 4.98 | 5.04 | 168.0 | 173.2 | 175.3 | 178.3 |
| 75% | 7.98 | 7.94 | 7.91 | 7.88 | 1.07 | 1.02 | 0.98 | 0.96 | 38.40 | 43.50 | 47.29 | 53.20 | 4.22 | 4.85 | 4.98 | 5.12 | 169.0 | 174.0 | 177.0 | 178.5 |
| 100% | 7.99 | 7.96 | 7.94 | 7.91 | 1.04 | 1.01 | 0.96 | 0.92 | 40.32 | 46.88 | 53.90 | 55.22 | 4.40 | 4.89 | 4.98 | 5.22 | 171.0 | 175.2 | 178.0 | 179.0 |
| F1 | LSD | | 0.07 | | LSD | | 0.13 | | LSD | | 2.27 | | LSD | | 1.32 | | LSD | | 11.33 | |
| | SL | | ns | | SL | | ns | | SL | | ** | | SL | | ns | | SL | | ns | |
| F2 | LSD | | 0.10 | | LSD | | 0.09 | | LSD | | 1.75 | | LSD | | 0.66 | | LSD | | 10.44 | |
| | SL | | ns | | SL | | ns | | SL | | *** | | SL | | * | | SL | | ns | |
| F1*F2 | | | ns | | F1*F2 | | ns | | F1*F2 | | * | | F1*F2 | | ns | | F1*F2 | | ns | |

**Remarks**: F1: main factor (application rates of the N-fertilizer), F2: sub-factor (time of magnetic treatment), LSD: least significant difference at $p \leq 0.05$, SL: Significance of Level, ns: non-significant

**Table 3.** Effect of the studied treatments on the available micronutrients (mg kg$^{-1}$) in the experimental soil

| The applied N-fertilization from the RD | Available concentration (mg kg$^{-1}$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fe | | | | Mn | | | | Zn | | | |
| | CL | Time of MT (min) | | | CL | Time of MT (min) | | | CL | Time of MT (min) | | |
| | | 15 | 30 | 45 | | 15 | 30 | 45 | | 15 | 30 | 45 |
| 50% | 1.90 | 1.94 | 1.97 | 1.99 | 1.04 | 1.06 | 1.09 | 1.14 | 0.55 | 0.57 | 0.59 | 0.61 |
| 75% | 1.93 | 1.97 | 1.98 | 2.03 | 1.07 | 1.12 | 1.18 | 1.22 | 0.58 | 0.59 | 0.63 | 0.66 |
| 100% | 1.95 | 1.98 | 2.05 | 2.10 | 1.10 | 1.16 | 1.23 | 1.26 | 0.62 | 0.65 | 0.68 | 0.72 |
| F1 | LSD | | 0.35 | | LSD | | 0.13 | | LSD | | 0.26 | |
| | SL | | ns | | SL | | ns | | SL | | ns | |
| F2 | LSD | | 0.16 | | LSD | | 0.16 | | LSD | | 0.19 | |
| | SL | | ns | | SL | | ns | | SL | | ns | |
| F1*F2 | | | ns | | F1*F2 | | ns | | F1*F2 | | ns | |

**Remarks**: F1: main factor (application rates of the N-fertilizer), F2: sub-factor (time of magnetic treatment), LSD: least significant difference at $p \leq 0.05$, SL: Significance of Level, ns: non-significant

The groundnut seeds and straw samples were oven-dried for 48 h at 70°C and ground. A half gram of the powdered seeds and/or straw was acid digested using the mixed $H_2SO_4/HClO_4$ (1:1). The N, P, and K concentrations available in soil were extracted by 1% $K_2SO_4$, 0.5 N $NaHCO_3$, and 1 N $NH_4OAc$ (pH 7.0), respectively. The nutrients' concentrations in the seeds and straw were estimated by distillation using a Kjeldahl apparatus (N), calorimetrically by the UV-Vis. Spectrophotometer (P) and by the flame photometer (K and Na). The chlorophyll content (mg $g^{-1}$ f.w) in the groundnut leaves was estimated according to the mentioned methods. All results were average values of the two seasons.

Nutrient use efficiency indices: they were calculated for the treatments according to Equations 1 and 2:

$$\text{Nutrient Use Efficiency (UE)} = \frac{(P_{nf}-P_{n0})}{\text{Fertilizerrate (N or Por K, kgha}^{-1})} \times 100 \ldots\ [1]$$

$$\text{Agronomic Efficiency (AE)} = \frac{Y_f-Y_0}{\text{Fertilizerrate (N or P or K, kgha}^{-1})} \ldots\ldots\ [2]$$

Where $P_{nf}$ = seed N and/or P and/or K in fertilized plots as (g $kg^{-1}$); $P_{n0}$ = seed N and/or P and/or K in non-fertilized plots as (g $kg^{-1}$); Y = seed yield (kg $ha^{-1}$).

### 2.1. Statistical analysis

The two-way analysis of variance (ANOVA) was carried out to compare among the treatments using the LSD at ($P \leq .05$). The Co-State software Package (Ver. 6.311) was used.

## 3. RESULTS

### 3.1. Effect of the studied treatments on some of the experimental soil properties

Table 2 and Table 3 indicate that the magnetically treated urea ($CO(NH_2)_2$) applied on soil (F1) and/or the treated groundnut seeds (F2) have resulted in non-significant variations in the soil pH, EC (dS $m^{-1}$), and the available K, Fe, Mn, and Zn (mg $kg^{-1}$). The concentrations of the soil available N and P (mg $kg^{-1}$) were significantly increased by 38.5 and 25.4% at the 75 and 50% N-fertilization with 45 min MT, respectively at $P \leq 0.05$, compared to its corresponding control (CL). The interactions of the F1 × F2 were non-significant for the mentioned soil properties except for the available N referring to F1 or F2 effects independent from each other.

### 3.2. Effect of the studied treatments on the yield and some vegetative parameters

According to Table 4 and Figure 1, the most significant increases in the plant height (cm), no. of pods/plant, and wt. pods/plant (g), were obtained by the 45 min MT with the 75% N-RD by 54.5, 84.8, and 51.78%, respectively and with the 100% N-RD by 66.8% for the wt. Seeds/plant (g) compared to its corresponding CL. The effects of F1 and/or F2 may be complementary to each other in case of the plant weight and the weight of grains/plant (g) as shown by their significant interaction at $P \leq 0.05$.

Significant increases in the 100-seeds weight (g), pods, and seeds yield (kg $ha^{-1}$) at $P \leq 0.05$ compared with the CL at the 45 min MT by 27.5 (75% N-RD), by 17.1, and 21.8% (100% N-RD), were observed in Table 5. The interaction of the F1 × F2 was significant for the 100 seeds weight and the pods yield. The relative increase in the yield (kg $ha^{-1}$) of pods and seeds due to the MT followed the order 45 min > 30 min > 15 min for the three N-rates 50, 75, and 100% of the N-RD fertilization.

### 3.3. Effect of the studied treatments on the total concentration (g $kg^{-1}$) of N, P, K, Na, and the Na/K ratio in the seeds and straw

The total concentration of N (g $kg^{-1}$) in Table 6 was increased significantly in the seeds by 9.7%, 33.1%, and 51.2% at the 100% rate for the 15, 30, and 45 min, respectively. The total concentrations of P and K (g $kg^{-1}$) in seeds showed non-significant variations at $P \leq 0.05$. The most significant increases in the P and K concentrations (g $kg^{-1}$) in the straw were by 9.2% with 100% and by 21.2% with 75% of the N-RD, respectively at the 30 min MT. The total Na concentration (g $kg^{-1}$) presented in Table 7 varied non-significantly in the seeds and significantly in the straw due to both the N-fertilization rates and magnetization of seeds pre-sowing compared to the corresponding CL at $P \leq 0.05$. The Na/K ratio in both seeds and straw showed significant but irregular variation as well as significant F1× F2 interactions.

**Table 4.** Effect of the studied treatments on some groundnut vegetative parameters

| The applied N-fertilization from the RD | No. of pods/Plant | | | | Wt. pods/Plant (g) | | | | Wt. seeds/Plant (g) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CL | Time of MT (min) | | | CL | Time of MT (min) | | | CL | Time of MT (min) | | |
| | | 15 | 30 | 45 | | 15 | 30 | 45 | | 15 | 30 | 45 |
| 50% | 18.9 | 24.3 | 30.2 | 33.7 | 38.3 | 45.9 | 53.1 | 58.4 | 22.9 | 26.3 | 30.1 | 37.5 |
| 75% | 22.4 | 29.6 | 37.3 | 41.4 | 42.1 | 49.6 | 57.9 | 63.9 | 24.6 | 28.6 | 32.1 | 40.1 |
| 100% | 24.4 | 30.1 | 37.9 | 42.2 | 45.7 | 54.3 | 62.3 | 67.4 | 27.1 | 31.5 | 39.9 | 45.2 |
| F1 | LSD | | 1.24 | | LSD | | 1.29 | | LSD | | 1.31 | |
| | SL | | *** | | SL | | *** | | SL | | *** | |
| F2 | LSD | | 1.66 | | LSD | | 1.14 | | LSD | | 1.14 | |
| | SL | | *** | | SL | | *** | | SL | | *** | |
| F1*F2 | | | ns | | F1*F2 | | ns | | F1*F2 | | ** | |

**Remarks**: F1: main factor (application rates of the N-fertilizer), F2: sub-factor (time of magnetic treatment), LSD: least significant difference at p ≤ 0.05, SL: Significance of Level, ns: non-significant

**Table 5.** Effect of the studied treatments on the groundnut pods and seeds yield (kg ha$^{-1}$)

| The applied N-fertilization from the RD | 100 seed wt. (g) | | | | Pods Yield (kg ha$^{-1}$) | | | | Seeds Yield (kg ha$^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CL | Time of MT (min) | | | CL | Time of MT (min) | | | CL | Time of MT (min) | | |
| | | 15 min | 30 min | 45 min | | 15 min | 30 min | 45 min | | 15 min | 30 min | 45 min |
| 50% | 76.72 | 57.48 | 56.39 | 67.82 | 3452.4 | 3619.0 | 3785.7 | 3881.0 | 2119.0 | 2261.9 | 2333.3 | 2428.6 |
| 75% | 61.54 | 74.18 | 75.29 | 78.48 | 3642.9 | 3857.1 | 4023.8 | 4095.2 | 2309.5 | 2357.1 | 2500.0 | 2619.0 |
| 100% | 74.74 | 52.04 | 66.43 | 65.62 | 3761.9 | 4071.4 | 4261.9 | 4404.8 | 2345.2 | 2571.4 | 2738.1 | 2857.1 |
| F1 | LSD | 6.55 | | | LSD | 65.44 | | | LSD | 130.88 | | |
| | SL | * | | | SL | *** | | | SL | ** | | |
| F2 | LSD | 4.67 | | | LSD | 57.18 | | | LSD | 93.37 | | |
| | SL | *** | | | SL | *** | | | SL | *** | | |
| F1*F2 | | *** | | | F1*F2 | *** | | | F1*F2 | ns | | |

**Remarks**: F1: main factor (application rates of the N-fertilizer), F2: sub-factor (time of magnetic treatment), LSD: least significant difference at p ≤ 0.05, SL: Significance of Level, ns: non-significant

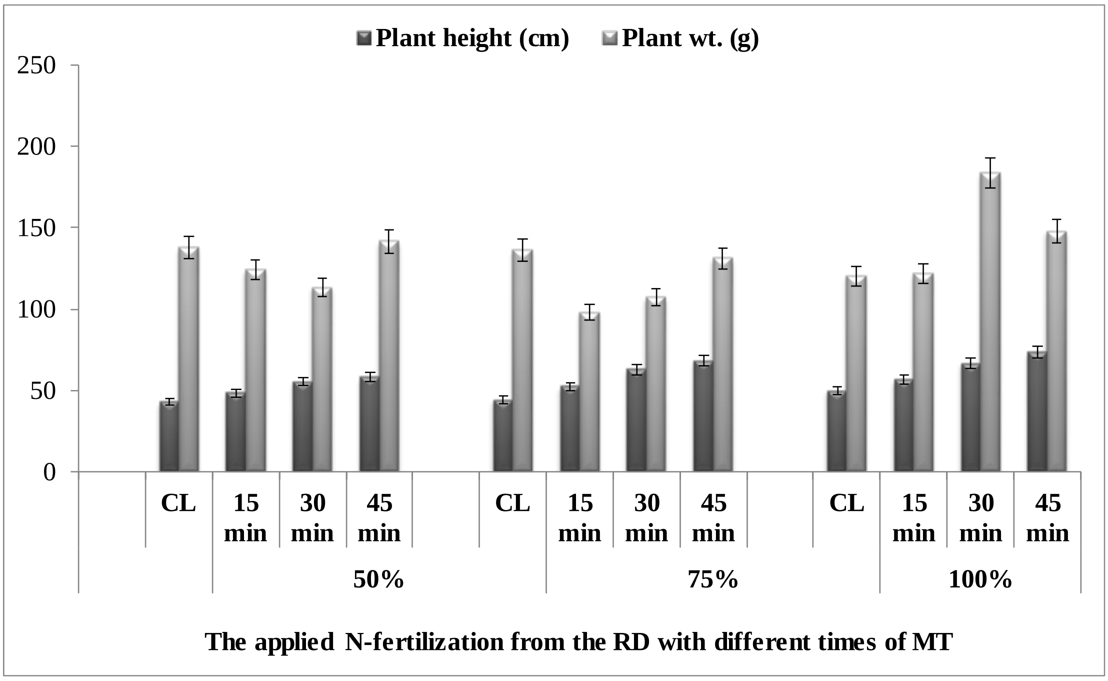


**Figure 1.** Effect of the studied treatments on the plant height (cm) and plant weight (g)

The use efficiency (UE) illustrated in Figure 2 shows that the 100% N-fertilization along with the 15 min MT before cultivation or the 50% and/or 100% N-fertilization along with the 30 min MT or the 50% along with the 45 min MT could be recommended. Otherwise, negative values for the NUE (%) or PUE (%) or KUE (%) are obtained that may be due to some abnormal changes and disturbed equilibrium of the nutrients absorption by plant resulted from the MT. At the 15-min time and 100% N-fertilization, the yield of pods and seeds (kg ha$^{-1}$) has increased relatively by 8.2% and 9.7% respectively, compared to the corresponding CL. At the 30-min time and 50% and 100% N-fertilization, the yield (kg ha$^{-1}$) has increased relatively by 9.7% and 13.3% respectively for the pods and by 10.1% and 16.8% respectively for the seeds. At the 45-min time and 50% N-fertilization, the yield (kg ha$^{-1}$) has increased by 12.4% and 14.6% for pods and seeds, respectively. The agronomic efficiency (AE) in Figure 3 was increased by the MT for the N, P, and K nutrients in the order 15 < 30 < 45 min at the 50, 75, and 100% N-fertilization rates.

### 3.4. The effect of the studied treatments on the chlorophyll content (mg g$^{-1}$ f.w) in the groundnut leaves

The magnetically treated N-fertilizer has significantly affected both the chlorophyll b and the total chlorophyll (mg g$^{-1}$ f.w) presented in Table 8. At the 100% N-fertilization with the 15 and 30 min of MT, the chlorophyll a has increased by 50.8 and 29.4%, the chlorophyll b increased by 103.7 and 37.0%, and the total chlorophyll (a + b) increased by 70.7 and 32.2%, respectively. However, the chlorophyll a/b ratio has decreased by 26.3 and 5.8% for the mentioned treatments. At the 45 min of MT, the chlorophyll a, b, and the total chlorophyll (a + b) were decreased by 1.6, 6.2, and 3.9%, respectively, while the chlorophyll a/b ratio was increased by 4.5%. The interactive effect of both F1 and F2 was significant for all the chlorophyll a, b, total chlorophyll (a + b) and the chlorophyll a/b ratio.

**Table 6.** Effect of the studied treatments on the total concentration of N, P, and K in the seeds and straw (g kg$^{-1}$)

| Total concentration (g kg$^{-1}$) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| The applied N-fertilization from the RD | | Seeds | | | | Straw | | | |
| | | N | | | | N | | | |
| | | CL | Time of MT (min) | | | CL | Time of MT (min) | | |
| | | | 15 min | 30 min | 45 min | | 15 min | 30 min | 45 min |
| 50% | | 36.86 | 32.31 | 40.27 | 37.94 | 25.20 | 8.87 | 22.40 | 19.60 |
| 75% | | 47.78 | 28.53 | 34.97 | 28.95 | 18.48 | 6.72 | 11.76 | 14.00 |
| 100% | | 24.85 | 27.27 | 33.08 | 37.58 | 18.48 | 10.08 | 21.16 | 11.20 |
| F1 | LSD | | | 0.04 | | LSD | | 19.49 | |
| | SL | | | *** | | SL | | ns | |
| F2 | LSD | | | 1.98 | | LSD | | 16.25 | |
| | SL | | | *** | | SL | | ns | |
| F1*F2 | | | | *** | | F1*F2 | | ns | |
| | | P | | | | P | | | |
| 50% | | 3.86 | 4.10 | 4.16 | 4.12 | 1.65 | 1.33 | 1.30 | 1.38 |
| 75% | | 4.16 | 4.15 | 4.08 | 4.53 | 1.53 | 1.20 | 1.13 | 1.05 |
| 100% | | 4.37 | 4.45 | 5.11 | 4.18 | 1.30 | 1.35 | 1.42 | 1.15 |
| F1 | LSD | | | 1.13 | | LSD | | 0.07 | |
| | SL | | | ns | | SL | | ** | |
| F2 | LSD | | | 1.04 | | LSD | | 0.10 | |
| | SL | | | ns | | SL | | *** | |
| F1*F2 | | | | ns | | F1*F2 | | ** | |
| | | K | | | | K | | | |
| 50% | | 4.61 | 5.06 | 5.52 | 4.75 | 7.61 | 12.33 | 6.56 | 5.44 |
| 75% | | 5.03 | 5.13 | 5.69 | 5.27 | 6.28 | 5.44 | 7.61 | 3.49 |
| 100% | | 5.13 | 6.00 | 5.52 | 4.93 | 6.77 | 6.28 | 5.87 | 7.19 |
| F1 | LSD | | | 1.13 | | LSD | | 0.65 | |
| | SL | | | ns | | SL | | ** | |
| F2 | LSD | | | 0.87 | | LSD | | 0.57 | |
| | SL | | | ns | | SL | | *** | |
| F1*F2 | | | | ns | | F1*F2 | | *** | |

**Remarks**: F1: main factor (application rates of the N-fertilizer), F2: sub-factor (time of magnetic treatment), LSD: least significant difference at $p \leq 0.05$, SL: Significance of Level, ns: non-significant

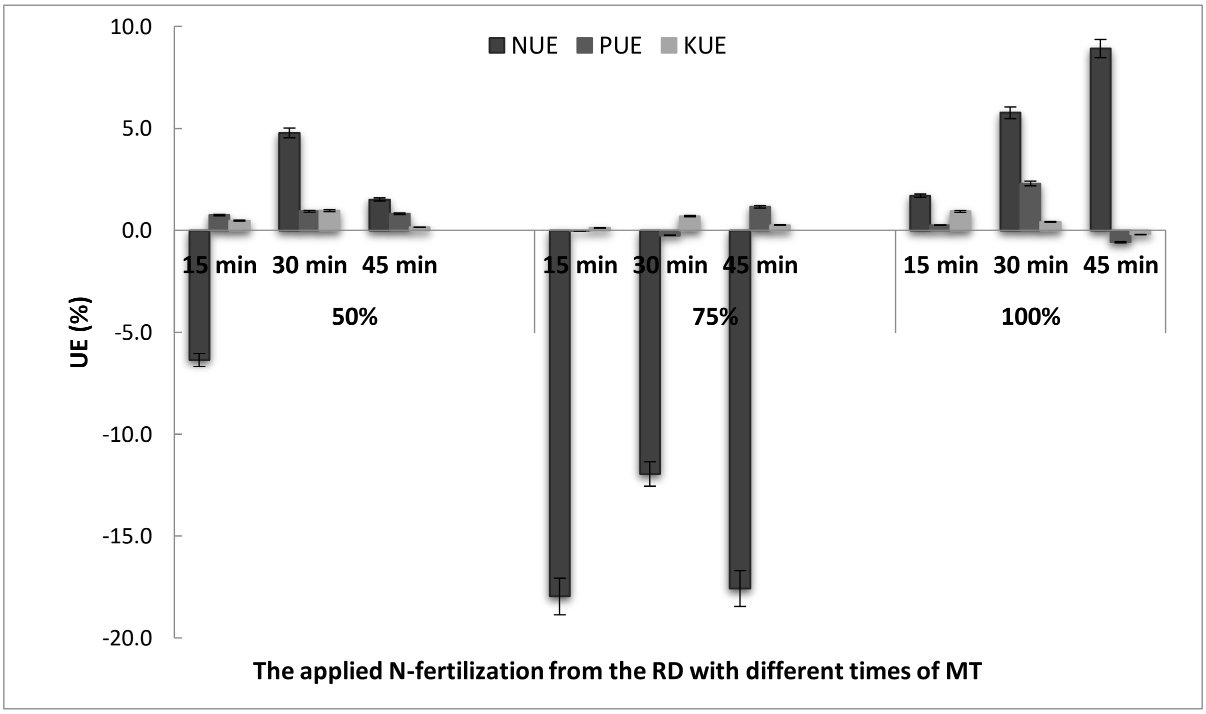


**Figure 2.** The nutrients use efficiency (NUE, %) affected by the studied treatments

**Table 7.** Effect of the studied treatments on the total concentration of Na and Na/K ratio in the seeds and straw (g kg$^{-1}$)

| The applied N-fertilization from the RD | Seeds | | | | | | | | Straw | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total Na+ concentration (g kg$^{-1}$) | | | | Na+ / K+ | | | | Total Na+ concentration (g kg$^{-1}$) | | | | Na+ / K+ | | | |
| | CL | Time of MT (min) | | | CL | Time of MT (min) | | | CL | Time of MT (min) | | | CL | Time of MT (min) | | |
| | | 15 min | 30 min | 45 min | | 15 min | 30 min | 45 min | | 15 min | 30 min | 45 min | | 15 min | 30 min | 45 min |
| 50% | 0.47 | 0.54 | 0.54 | 0.50 | 0.10 | 0.11 | 0.10 | 0.11 | 0.22 | 0.24 | 0.22 | 0.14 | 0.03 | 0.02 | 0.03 | 0.03 |
| 75% | 0.47 | 0.65 | 0.43 | 0.58 | 0.09 | 0.13 | 0.08 | 0.11 | 0.14 | 0.22 | 0.22 | 0.22 | 0.02 | 0.04 | 0.03 | 0.06 |
| 100% | 0.61 | 0.22 | 0.61 | 0.54 | 0.12 | 0.04 | 0.11 | 0.11 | 0.22 | 0.43 | 0.16 | 0.22 | 0.03 | 0.07 | 0.03 | 0.03 |
| F1 | LSD | | 0.065 | | LSD | | 0.007 | | LSD | | 0.005 | | LSD | | 0.011 | |
| | SL | | ns | | SL | | * | | SL | | *** | | SL | | ns | |
| F2 | LSD | | 0.057 | | LSD | | 0.010 | | LSD | | 0.004 | | LSD | | 0.009 | |
| | SL | | ns | | SL | | * | | SL | | *** | | SL | | ** | |
| F1*F2 | | | *** | | F1*F2 | | *** | | F1*F2 | | *** | | F1*F2 | | *** | |

**Remarks**: F1: main factor (application rates of the N-fertilizer), F2: sub-factor (time of magnetic treatment), LSD: least significant difference at p ≤ 0.05, SL: Significance of Level, ns: non-significant

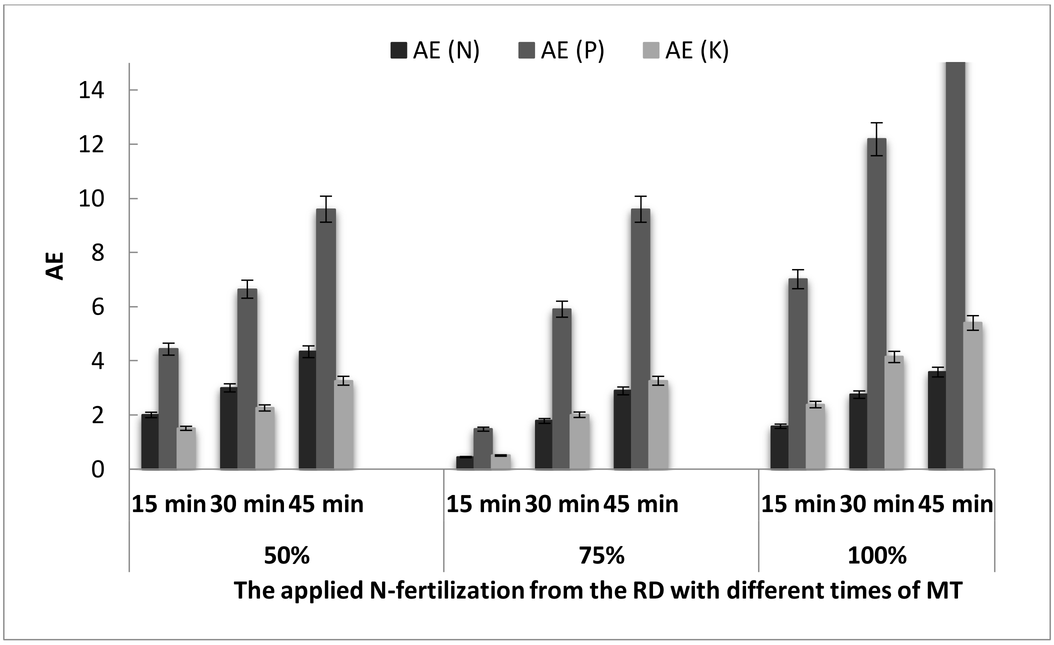


**Figure 3.** Agronomic efficiency (AE) of different nutrients affected by the studied treatment

## 4. DISCUSSION

Application of a mineral fertilizer to the soil releases the nutrients like N, P, and K to be available for the plant uptake via the soil solution. The buffering action of soil as well as the chemical equilibria control the balance of ions depending on the soil conditions. The comparison between the control treatments with these of the magnetically treated N-fertilizer indicates a different behaviour of the estimated properties. Variations in the soil pH, EC, and available P, K, Fe, Mn, Zn (Tables 2 & 3) were non-significant perhaps because of the buffering action and the chemical equilibria within the soil matrix. The response of the solid, liquid and gas phases of soil along with water-soluble nutrients to the magnetic induction created by the magnetically treated urea depends on the soil conditions (Al-Ghamdi, 2020; Okba et al., 2022).

The effect of the MT on the groundnut seeds was independent of that on the N-fertilizer showing non-significant variations in Tables 2 and 3. However, the combination between the MT of the seeds and the N-fertilizer significantly increased the N availability in soil and uptake by groundnut seeds. The interactive significant effect of the MT of the seeds and the N-fertilizer is strongly reflected in the estimated yield and yield parameters in tables 4 and 5 (El-Basioni et al. (2015), Hafeez et al. (2023), Bairwa et al. (2023), Altalib et al. (2022), Nile et al. (2022)). As well, it showed an almost significant effect on the uptake of the P and K nutrients along with the Na/K ratio in the seeds and/or the straw (Tables 6 and 7). The chlorophyll type (Fig. 4) and content in table 8 was also affected significantly by both the MT of the seeds and the fertilizer. The MT for 30 min may be suitable to provide an acceptable positive N, P, and K use efficiency as indicated by Figure 2 . The magnetic susceptibility $\chi_m$ ($10^{-6}$ cm$^3$ mol$^{-1}$) as an indicator of the magnetism can be responsible for the behaviour of a material when it is induced by a MF.

**Table 8.** Effect of the studied treatments on the chlorophyll content (mg $g^{-1}$ f.w) in the groundnut leaves

| The applied N-fertilization from the RD | Chl a (mg $g^{-1}$ f.w) | | | | Chl b (mg $g^{-1}$ f.w) | | | | Total Chl (mg $g^{-1}$ f.w) | | | | Chl a/b | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CL | Time of MT (min) | | | CL | Time of MT (min) | | | CL | Time of MT (min) | | | CL | Time of MT (min) | | |
| | | 15 min | 30 min | 45 min | | 15 min | 30 min | 45 min | | 15 min | 30 min | 45 min | | 15 min | 30 min | 45 min |
| 50% | 1.39 | 1.25 | 1.23 | 1.56 | 0.99 | 0.72 | 0.69 | 1.01 | 2.37 | 1.98 | 1.93 | 2.57 | 1.40 | 1.74 | 1.78 | 1.54 |
| 75% | 1.74 | 1.11 | 1.30 | 1.67 | 1.40 | 0.70 | 0.91 | 1.31 | 3.14 | 1.81 | 2.21 | 2.98 | 1.24 | 1.59 | 1.43 | 1.27 |
| 100% | 1.26 | 1.90 | 1.63 | 1.24 | 0.81 | 1.65 | 1.11 | 0.76 | 2.08 | 3.55 | 2.75 | 2.00 | 1.56 | 1.15 | 1.47 | 1.63 |
| F1 | LSD | | 0.13 | | LSD | | 0.13 | | LSD | | 0.26 | | LSD | | 0.23 | |
| | SL | | ns | | SL | | * | | SL | | * | | SL | | ns | |
| F2 | LSD | | 0.11 | | LSD | | 0.21 | | LSD | | 0.20 | | LSD | | 0.17 | |
| | SL | | ns | | SL | | ns | | SL | | ns | | SL | | ns | |
| F1*F2 | | | *** | | F1*F2 | | *** | | F1*F2 | | *** | | F1*F2 | | ** | |

**Remarks**: F1: main factor (application rates of the N-fertilizer), F2: sub-factor (time of magnetic treatment), LSD: least significant difference at p ≤ 0.05, SL: Significance of Level, ns: non-significant

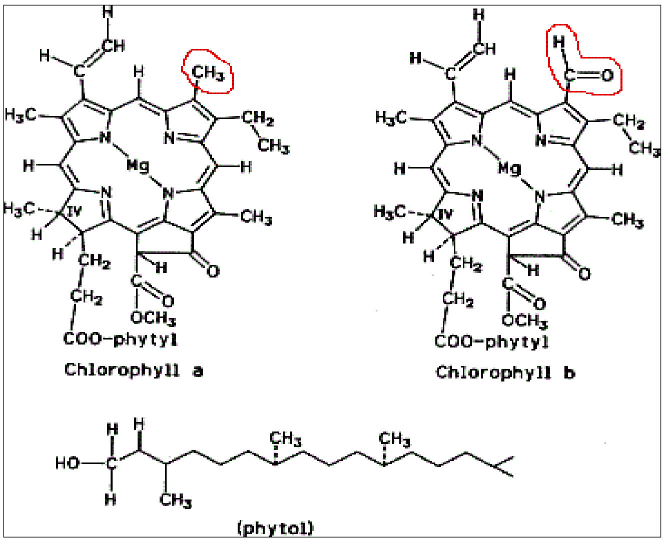

**Figure 4.** Structural formula of chlorophyll a and b

Measurable values of the susceptibility $\chi_m$ were provided in the literature. It is difficult to predict the magnetic response of the fertilizer or the nutrients within the soil or plant matrix because of the complex chemical and biological processes in the soil solution and plant cells (Wang et al., 2018). Ions of Potassium (K), Iron (Fe), Manganese (Mn), and perhaps the Nitrate ($NO_3^-$) and Phosphate ($PO_4^{-3}$) may possess positive susceptibility $\chi_m$. In the soil-plant system, the magnetic susceptibility $\chi_m$ of different constituents, magnetic induction created by the magnetically treated fertilizer or seeds, and the resulted magnetic attraction/repulsion forces are factors expected to control the equilibria of the chemical and biological reactions. It may work in the energy spectrum of plants and affects the balanced uptake of nutrients by the plant. Under a MF, the electrons in the orbitals of an atom become distorted and the gap between the different lines depends on the strength of the MF. Magnetic fertilizers were believed to manage and harmonize the molecular structure of the soil (Li et al., 2021; Vasilyeva et al., 2021). Multi-component magnetic fertilizer studied previously had been shown to strengthen the magnetic and energetic field around plants for both the grain and crops. The growth parameters were also enhanced significantly in plants from the magnetically treated seeds (Iqbal et al., 2016).

## 5. CONCLUSION

The magnetic treatment (MT) of the nitrogen fertilizer as well as the groundnut (*Arachis hypogaea* L.) seeds before cultivation has increased the yield and enhanced the quality of the crop under sandy soil conditions. It enhanced the N, P, and K nutrients uptake and their use efficiency (UE) in the soil-plant system. The total concentration of N (g $kg^{-1}$) was increased significantly in the seeds at the 100% fertilization rate by the MT for 15, 30, and 45 min. The 100% N-fertilization along with 15 min MT before cultivation or the 50% and/or 100% N-fertilization along with 30 min MT or the 50% along with the 45 min MT can be recommended. The magnetic force affected the fertilizer and the seeds may induce the chemical and/or biological reactions during the plant growth. The MT of fertilizers and/or seeds before cultivation can be a good option to improve the crops productivity under some conditions. A suggested focal point for further research may be some intensified studies on the effect of the MT on different chemical forms of the N, P, and K mineral fertilizers and its relation with the nutrients agronomic and use efficiencies (AE and NUE). Also, intensified studies on the effect of the MT of seeds before cultivation for different crops' species under different soil conditions regarding the quantitative and qualitative yield attributes. Factors such as the time of the MT, intensity of the MF used along with the class of soil and plant to be studied shall be taken into consideration.

## Declaration of Competing Interest

The authors declare that no competing financial or personal interests that may appear and influence the work reported in this paper.

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