Effect of High-frequency electromagnetic radiation on germination of Wheat (*Triticum aestivum* L.)

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***Abstract*—High-frequency electromagnetic radiation refers to the part of the electromagnetic spectrum with relatively short wavelengths and high frequencies including non-ionizing radio waves emitted by cell phones. The widespread use of cell phones has led to an increase in electromagnetic field (EMF) pollution, also known as EMF smog. While many studies have focused on the potential impact of EMF on human health, the effects of cell phone EMF radiation on plant germination, growth and biochemical changes have received less attention. The intensity and frequency of the EMF, as well as the duration of exposure, can influence the observed effects on plants. Additionally, different plant species may respond differently to EMF exposure. Effect of cell phone electromagnetic radiation (power density: 8.47 µW cm^{-2}; 900 MHz band width; for ½, 1 and 2 h) on germination parameters of Wheat (*Triticum aestivum* L.) was investigated in the present study. Results suggested that exposure to cell phone electromagnetic field radiation (EMF) has a negative impact on seed germination when exposed for 1 hour or more. This finding is consistent with some studies that have reported altered seed germination rates under electromagnetic radiation exposure. Further research is going on for better understanding the mechanisms underlying these effects and to determine the extent to which EMF pollution from cell phones may be impacting the environment and ecosystems.**

***Keywords*: High-frequency, EMF smog, Wheat (*Triticum aestivum* L.), germination parameters**

I. Introduction

Wheat is a grass that is widely cultivated for its seed, which is a cereal grain used as a staple food in many countries around the world [1]. Wheat belongs to the Triticum genus and the Poaceae (or Gramineae) family, which includes various species of grasses. Wheat has been cultivated for thousands of years and is one of the most important cereal crops globally, along with rice and maize. The popularity of wheat can be attributed to its versatility, nutritional value, and ability to grow in a wide range of climates and soils. Wheat is not only a rich source of carbohydrates but also provides essential nutrients like protein, fiber, vitamins (particularly B vitamins), and minerals [2]. As a staple food, wheat plays a vital role in global food security and has a significant impact on the economy, environment, and human health. Increasing use of cell phones and other wireless communication devices has led to a rise in radio frequency (RF) waves in the atmosphere. These RF waves, also known as electromagnetic radiation, are a type of non-ionizing radiation. There have been concerns about the potential health effects of long-term exposure to RF waves on living organisms, including plants. Some studies suggest that exposure to RF radiation may have morphological and biochemical effects on plants [3],[4]. However, the scientific consensus on the impact of RF radiation on plants, remains inconclusive. Continued research is essential to better understand the potential long-term effects of radio frequency (RF) radiation on highly valued crops including Wheat.

II. Material and Methods

Plant material

Wheat seeds (Triticum aestivum L.); variety-HD 3117, India) were collected from Division of Seed Science and Technology, ICAR-IARI, New Delhi.

Soil Sample

Soil sample was collected from regions adjoining Noamundi Iron Mines, Noamundi, Jharkhand. The soil samples were analyzed (Table 1) and used in the experiment after sieving.

Table 1: Analysis result for soil sample collected from region adjoining Noamundi Iron Mines, Noamundi, Jharkhand.

Location	Soil type	Taxonomic group	pH[a]	Organic Carbon[b] (%)	Total Nitrogen[c] (mg.kg^{-1})	Phosphorus[d] (mg.Kg^{-1})	Potassium[e] (mg.Kg^{-1})	Iron[f] (mg.Kg^{1})
Noamundi Iron Mines, Noamundi, Jharkhand	Laterite	Haplustulf	6.35	0.49	345	< 3	77	< 5

[a] Measured by taking 1:1.25 soil water ratio by Elico-digital pH meter
[b] Determined by Walkey-Black method
[c] Estimated by Kjeldal method
[d] Estimated by Bray's No.1 method
[e] Estimated by Platenic-chloride gravimetric method
[f] Estimated by Citrate dithionite-bicarbonate method

Treatment of High-frequency electromagnetic radiation

The experimental setup involved the use of a shielded chamber designed to act as a Faraday cage [5], following the pattern of a Mode Stirred Reverberation Chamber (MSRC). A thermocol chamber with plywood support with all its walls completely layered with Faraday Fabric was designed and constructed to achieve an environment free from outside EMF interferences. The Faraday Fabric (thickness: 0.09 mm and surface resistance: < 0.05) purchased from J J CARE, USA, was a military grade shielding fabric made of polyester fiber, metallic copper, and metallic nickel (Fig 1). Two GSM cell phones operating at the 900 MHz frequency band, with modulated voice and low-frequency signals of 217 Hz and 8.34 Hz, respectively were used in the present study [6]. Cell phones were placed inside the chamber (47.5 cm x 27 cm x 17.5 cm) to expose them to a homogeneous electromagnetic field. The exposure parameters included a field strength of 5.5 V/m and an average power density (Pd) of 8.47 µW/cm² measured using a RF meter (GQ EMF-390, USA). Cell phones were used in talk mode, with earphones attached. This arrangement simulates a real-world scenario where cell phones are actively transmitting and receiving RF signals during a call. The goal is to study the potential effects of RF exposure on the samples associated with the experiment. To ensure continuous operation during the exposure period, the phone batteries were connected to a 12 V DC, 220 V AC adapter. The adapter was placed 2 meters away from the cell phones to minimize any interference or impact on the exposure conditions inside the chamber.

(a) (b)

Fig. 1: (a & b): Shielded chamber for RF electromagnetic radiation exposure

A set of hundred seeds soaked in distilled water for 8 hours was placed in a Petri dish with a diameter of 8.5 cm. These Petri dishes were positioned between the cell phones at approximately 8 cm. The seeds were exposed to RF radiation from the cell phones for varying durations: ½ hour, 1 hour or 2 hours. A control group was also included in the experiment. In this case, another set of 100 seeds was placed inside a separate chamber without cell phones, ensuring no RF exposure for this group. The control group helped account for any changes or effects that may occur due to factors other than the RF exposure. Efforts were made to eliminate all other electromagnetic field radiation (EMF) sources both inside and outside the exposure laboratory during the exposure treatment to ensure that the observed effects on the seeds can be attributed solely to the RF radiation from the cell phones. Additionally, both the exposure chamber (with cell phones) and the control chamber (without cell phones) were maintained at a constant room temperature of 25°C.

Germination studies

Exposed seeds were allowed to germinate in plastic trays containing the soil for a period of fourteen days with constant temperature, humidity, and light. The experiments were carried out in triplicate to ensure consistent results and to establish the reliability of the findings.

Evaluation of germination parameters

The germination parameters were calculated a s follows:

Germination percentage (GP)

Germination percentage is an important indicator of seed quality and viability. It helps determine the proportion of seeds in a population that are capable of successfully germinating under specific conditions. The equation to calculate germination percentage [7] is given by:

$$GP = \frac{\sum_{i=1}^{k} n_i}{N} \times 100$$

n_i= number of seeds germinated in the *i*th time

N= Total number of seeds used

Relativized percentage (RV)

Relativized percentage (RV) is used to compare the germination rates of different seed populations, treatments, or environmental conditions. It allows to understand the relative effectiveness of various factors on seed germination by comparing the germination percentages of different groups against a control group. The germination percentage can be relativized by the following equation [8]:

$$R\ (\%) = AP/HP\ X100$$

AP= actual percentage

HP= highest percentage amongst the group of data

This standardization allows comparisons among treatments equivalent when the amount of dormancy broken varied

Mean germination time (MGT)

Mean germination time (MGT) is a useful metric in seed germination studies that represents the average time required for a seed population to germinate. MGT provides insights into the speed of germination and can be used to compare the germination rates of different seed populations. The following formula was used to calculate the mean germination time [9]:

$$\bar{t} = \frac{\left(\sum_{i=1}^{k} n_i t_i\right)}{\left(\sum_{i=1}^{k} n_i\right)}$$

$n_i t_i$= The product of seeds germinated at interval *i*th with the corresponding time interval

n_i= number of seeds germinated in the *i*th time

Mean germination rate (MGR)

The mean germination rate (MGR) is the reciprocal of the mean germination time (MGT). The mean germination rate represents the average speed at which seeds germinate within a given population. MGR is calculated from MGT as shown below [10]

$$\bar{v} = \frac{1}{\bar{t}}$$

$\bar{t}$ = Mean germination time

Uncertainty of germination process (U)

Uncertainty of the germination process (U) is a metric used to assess the variability or dispersion of germination times within a seed population. It provides insight into the consistency of germination rates and can be used to compare the uniformity of germination among different seed populations, treatments, or environmental conditions. A lower value of U indicates more uniform and synchronized germination, while a higher value suggests greater variability in germination times. Uncertainty is calculated using the following equation [11]

$$U = \sum_{i=1}^{k} f_i \log_2 f_i$$

$$f_i = \frac{n_i}{\sum_{i=1}^{k} n_i}$$

fi= Relative frequency of germination

Synchrony of germination process (Z)

Synchrony of the germination process (Z) is a metric used to evaluate the level of synchronization or uniformity in germination times among a seed population. It is calculated using the following formula [11]:

$$Z = \frac{\sum_{i=1}^{k} C_{n_i,2}}{C_{\Sigma n_i,2}}$$

$C_{n_i,2} = n_i(n_i - 1)/2$

$C_{n_i,2}$= combinations of seeds germinated in the *i*th time, two by two.

n_i= number of seeds germinated in the *i*th time

Coefficient of variation of germination time (CVt)

The coefficient of variation of germination time (CVt) is a metric used to evaluate the relative variability or dispersion of germination times within a seed population. It is expressed as a percentage and provides insights into the consistency of germination rates. It is calculated by the following formula [10]

$$CVt = \frac{S_t}{\bar{t}} \times 100$$

S_t= standard deviation of germination time and calculated as

$$S_t = \sqrt{\frac{\sum_{i=1}^{k} n_i (t_i - \bar{t})^2}{\sum_{i=1}^{k} (n_i - 1)}}$$

$\bar{t}$ = mean germination time

Germination index (GI)
The germination index (GI) is a measure of the germination rate of a population of seeds, taking into account both the percentage of germinated seeds and the time taken for germination. It is expressed as [12]

$$GI = \frac{\sum_{i=1}^{k} n_i}{t_i}$$

n_i= number of seeds germinated in the ith time
t_i= time taken for seeds to germinate at the ith count

Coefficient of the velocity of germination (CVG)
The coefficient of the velocity of germination (CVG) is used to assess the vigor and speed of germination in a seed population. was calculated using the following formula [13]

$$CVG = \frac{\sum_{i=1}^{k} n_i t_i}{\sum_{i=1}^{k} n_i} \times 100$$

Mean daily germination percent (MDG)
Mean daily germination percent (MDG) is used to evaluate the average germination success of a seed population daily. It provides insights into the daily germination performance and can be used to compare different seed populations, treatments, or environmental conditions. It is calculated using the following expression [14]

$$MDG = \frac{GP}{T_n}$$

GP= final cumulative germination percentage
T_n= total number of intervals required for final germination
Peak value (PV)

The peak value (PV) is a metric used to identify the highest germination rate observed during the germination process. It indicates the time point at which the maximum number of seeds germinated and provides insights into the overall germination performance. It is computed as the maximum quotient obtained by dividing successive cumulative germination values by the relevant incubation time [14]

Germination value (GV)
Germination value (GV) is a metric that combines germination rate and the speed of germination to evaluate the overall performance of a seed population during germination. It can be calculated as described by [15]

$GV = MDG \times PV$
MDG= mean daily germination
PV= peak value or largest quotient obtained when all the cumulative germination percentages were divided by the respective time interval.

Statistical Tools
Results were calculated as mean ± standard deviation. Different letters (a–c) denote the significant differences among the group between the mean at $p < 0.05$ using one-way analysis of variance (ANOVA), Tukey's HSD test, and Scheffe's test using R-statistical tool version 4.2.2 and R-Studio version 2023.03.0-386.

III. RESULTS AND DISCUSSION

Germination percentage (GP) was highest for control seeds (Table 2), followed by seeds treated for 0.5 hours. Germination percentage decreased in a time dependent manner. Specifically, the GP was reported as 76.67% for untreated seeds and 76.33% for seeds treated for 0.5 hours. While seeds treated for 1 hour showed decreased GP of 69.00%, the least GP of 61.00% found in seeds treated for 2 hours (Fig 2). The study utilized the relativized percentage as a metric to compare germination performance of various seed lots or populations under different treatment exposure durations. The findings indicated that seeds not subjected to any treatments demonstrated a higher relativized percentage, implying better germination performance. As seen in Figure 3, there was a negative correlation between exposure duration and relativized percentage. This suggests that longer exposure durations to the treatments adversely impacted seed germination. The decline in germination performance could be attributed to various factors, such as stress induced by the treatments or changes in the physiological processes of the seeds. Mean Germination Time (MGT) was reduced in control seeds compared to treated seeds, indicating a faster and more synchronized germination process for seeds that were not subjected to any treatments. The MGT for control seeds was 5.05 days, while it was 5.06 days for seeds treated for 0.5 hours. In contrast, MGT increased to 5.36 days and 5.52 days for seeds treated for 1 hour and 2 hours, respectively (Fig 4). This observation suggested that the germination process is affected by the treatments, with longer exposure durations leading to slower germination.

A shorter MGT indicates faster germination and can be beneficial for agricultural applications, as it can improve crop establishment and ultimately yield. Mean Germination Rate (MGR) was higher for untreated control seeds compared to treated seeds, indicating better germination performance in the absence of treatments. The highest MGR value was 0.20 days for both control seeds and seeds treated for 0.5 hours. In comparison, MGR values were lower at 0.19 days and 0.18 days for seeds treated for 1 hour and 2 hours, respectively (Fig 5). This trend suggests that seed treatments, particularly at longer exposure durations, may have a negative impact on germination rate.

Table 2- Estimation of Germination Percentage (G%), Relativized Percentage (RP), Mean Germination Time (MGT) and Mean Germination Rate (MGR) of different treatments. Different letters (a–c) among the group denote the significant differences between the mean at $p < 0.05$ using one-way analysis of variance (ANOVA), Tukey's HSD comparison test, and Scheffe's test.

Treatment	Germination Percentage (G%) [%]	Relativized Percentage (RP) [%]	Mean Germination Time (MGT) [day]	Mean Germination Rate (MGR) [day^{-1}]
Control	76.67 ± 0.05^{a}	99.57 ± 0.06^{a}	5.05 ± 0.02^{a}	0.20 ± 0.001^{a}
900MHz-0.5 H	76.33 ± 0.09^{a}	99.13 ± 0.12^{a}	5.06 ± 0.04^{a}	0.20 ± 0.002^{a}
900MHz-1 H	69.00 ± 0.08^{b}	89.61 ± 0.11^{b}	5.36 ± 0.00^{a}	0.19 ± 0.00^{a}
900MHz-2 H	61.00 ± 0.08^{b}	79.22 ± 0.11^{c}	5.52 ± 0.00^{a}	0.18 ± 0.00^{a}

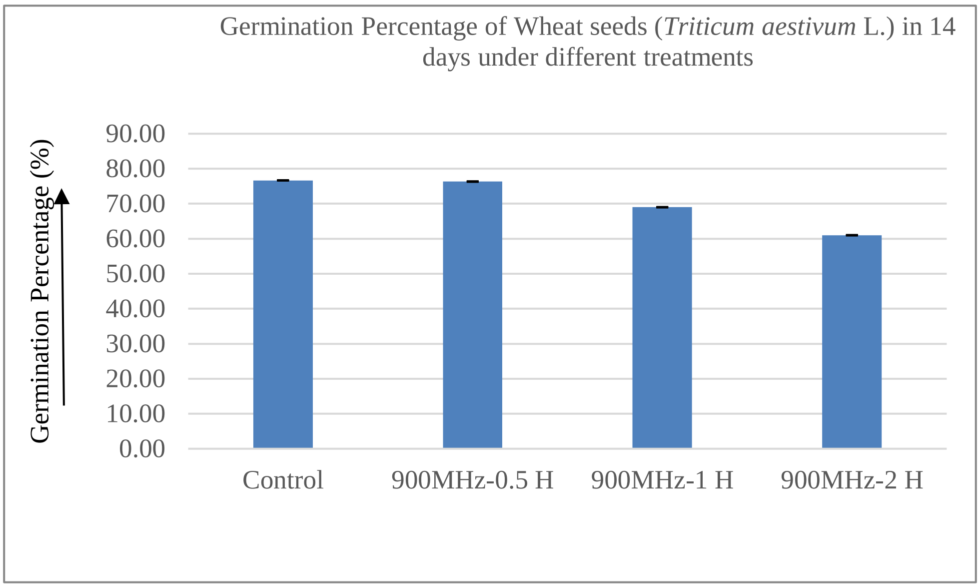

Fig.2: Germination Percentage of Wheat seeds

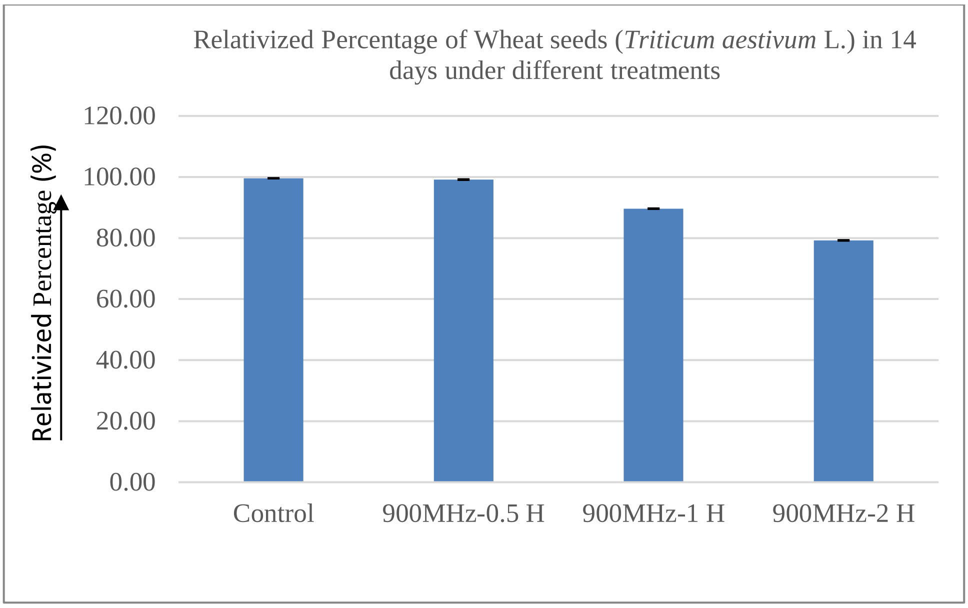

Fig.3: Relativized Percentage of Wheat seeds

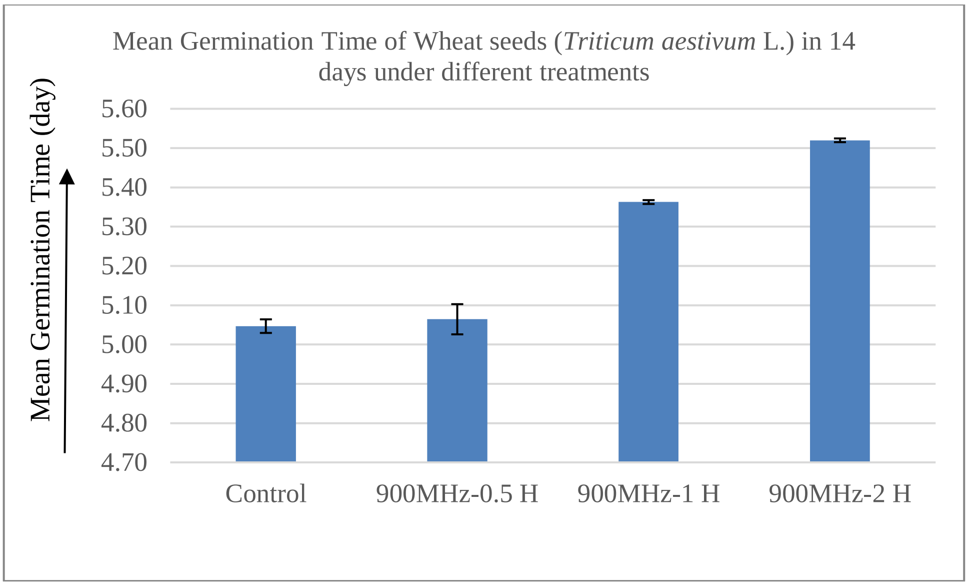

Fig.4: Mean Germination Time of Wheat seeds

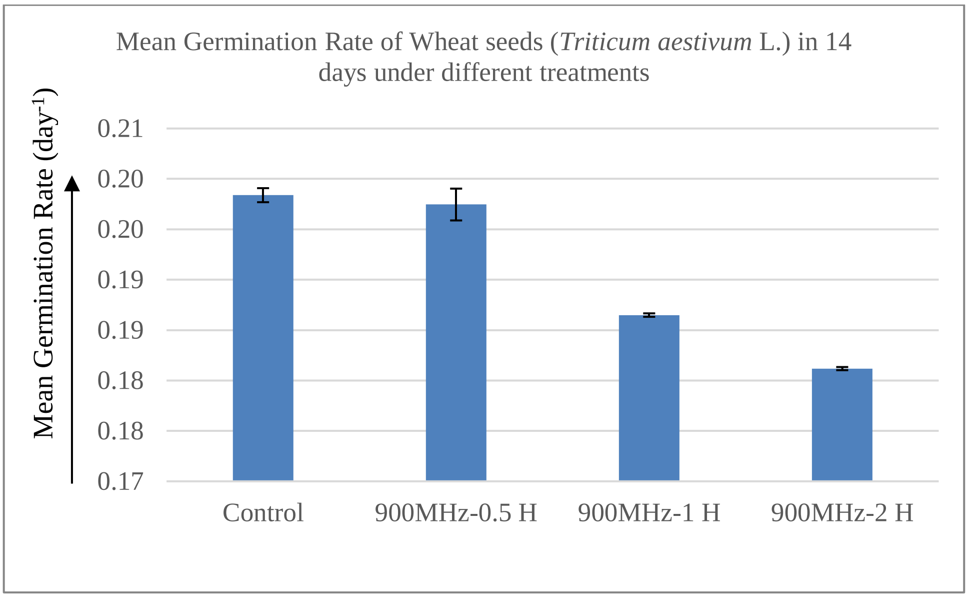

Fig.5: Mean Germination Rate of Wheat seeds

The coefficient of variation of germination time (CVt) is a useful measure to assess the variation or spread in the time taken for seeds to germinate within a group. The observed significant difference in CVt between the control and treated seeds (Fig 6) implies that exposure to high frequency electromagnetic fields may have impacted the germination process (Table 3). The coefficient of velocity of germination (CVG) [11] gives an indication of the rapidity of germination. In the study, untreated seeds and seeds treated for 0.5 hours exhibited higher CVG values (19.84 and 19.86, respectively) compared to seeds treated for 1 hour (18.65) and 2 hours (18.12). This suggests that the untreated seeds and those treated for shorter durations (0.5 hours) experienced faster and more efficient germination compared to the other groups (Fig 7). The observed trend indicates that treatment exposure duration plays a crucial role in determining the germination performance of seeds. The Germination Index (GI) is a valuable metric that considers both the percentage of germination occurring and the speed of the germination process. A significant difference between the experimental and control sets was observed for GI (Fig 8). Untreated seeds exhibited the highest GI value of 15.98 days, indicating the best germination performance among the groups. Seeds treated for 0.5 hours followed closely with a GI value of 15.64 days. However, the GI values decreased for seeds treated for 1 hour and 2 hours, recorded at 13.09 days and 11.14 days, respectively, suggesting reduced germination performance with longer treatment durations. A higher GI value indicates a higher percentage and a higher rate of germination [16]. A linear relationship was observed between the values of Uncertainty process (U) and the treatment conditions (Fig 9). This suggests that as the treatment conditions change, such as varying treatment exposure durations, the uncertainty in the germination process changes in a predictable, linear manner.

Table 3- Estimation of Coefficient of Variation of germination time (CVt), Coefficient of Velocity of germination time (CVG), Germination Index (GI) and Uncertainty of germination process(U) of different treatments. Different letters (a–c) among the group denote the significant differences between the mean at $p < 0.05$ using one-way analysis of variance (ANOVA), Tukey's HSD comparison test, and Scheffe's test.

Treatment	Coefficient of Variation of germination time (CVt) [%]	Coefficient of Velocity of germination time (CVG) [%]	Germination Index (GI) [day]	Uncertainty of germination process(U) [bit]
Control	23.88 ± 0.14^{a}	19.84 ± 0.07^{a}	15.98 ± 0.04^{a}	1.69 ± 0.01^{a}
900MHz-0.5 H	17.94 ± 0.22^{b}	19.86 ± 0.09^{a}	15.64 ± 0.13^{a}	1.67 ± 0.02^{a}
900MHz-1 H	12.61 ± 0.05^{c}	18.65 ± 0.02^{a}	13.09 ± 0.02^{b}	1.38 ± 0.00^{ab}
900MHz-2 H	9.09 ± 0.01^{c}	18.12 ± 0.02^{a}	11.14 ± 0.02^{b}	0.99 ± 0.00^{b}

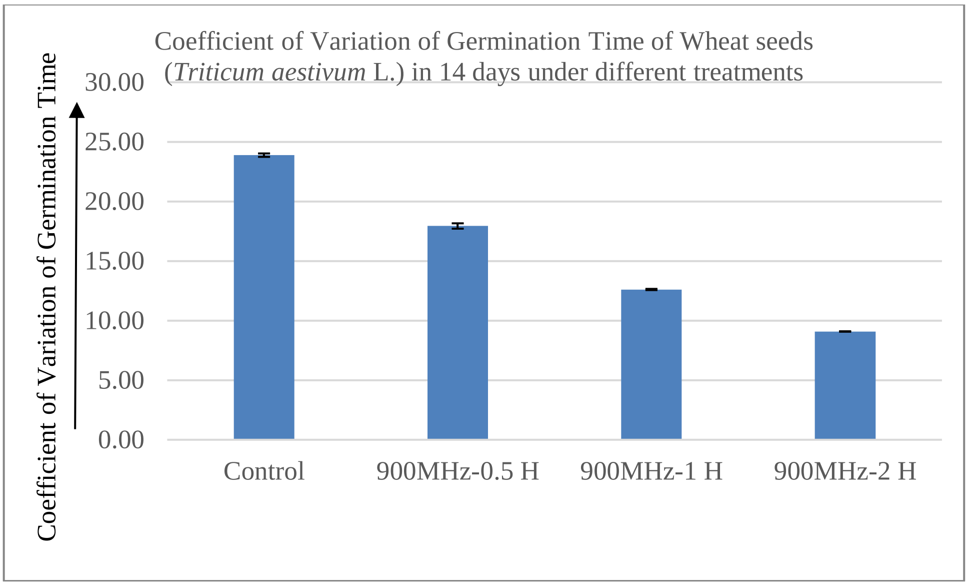

Fig.6: Coefficient of Variation of Germination Time of Wheat seeds

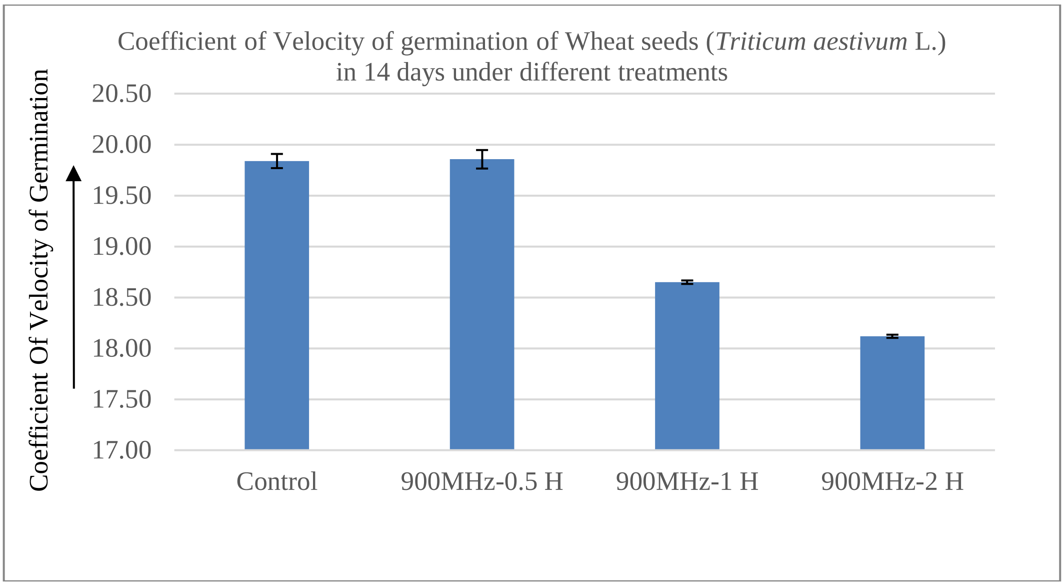

Fig.7: Coefficient of Velocity of Germination Time of Wheat seeds

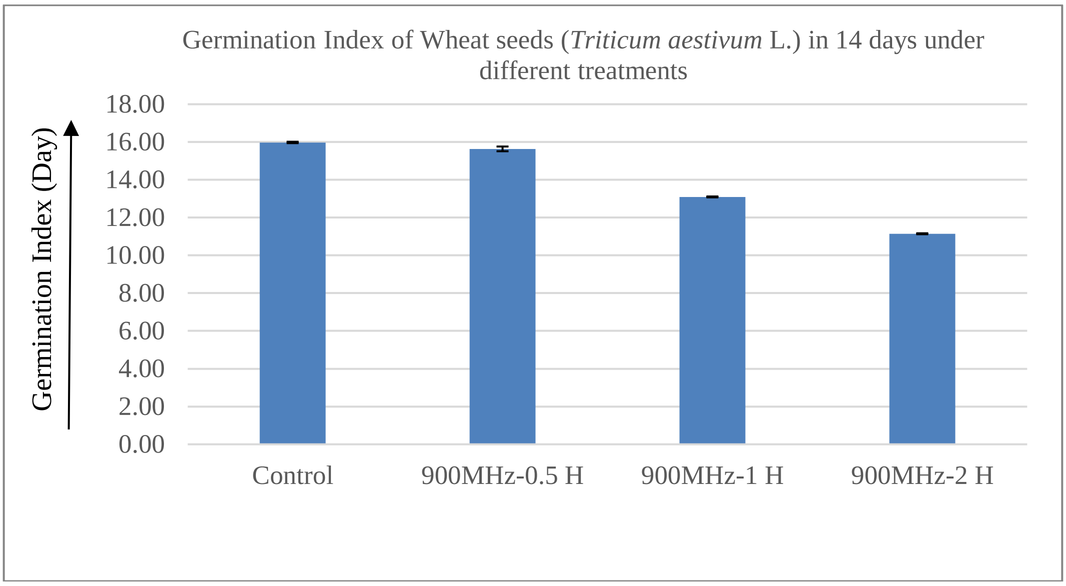

Fig.8: Germination Index of Wheat seeds

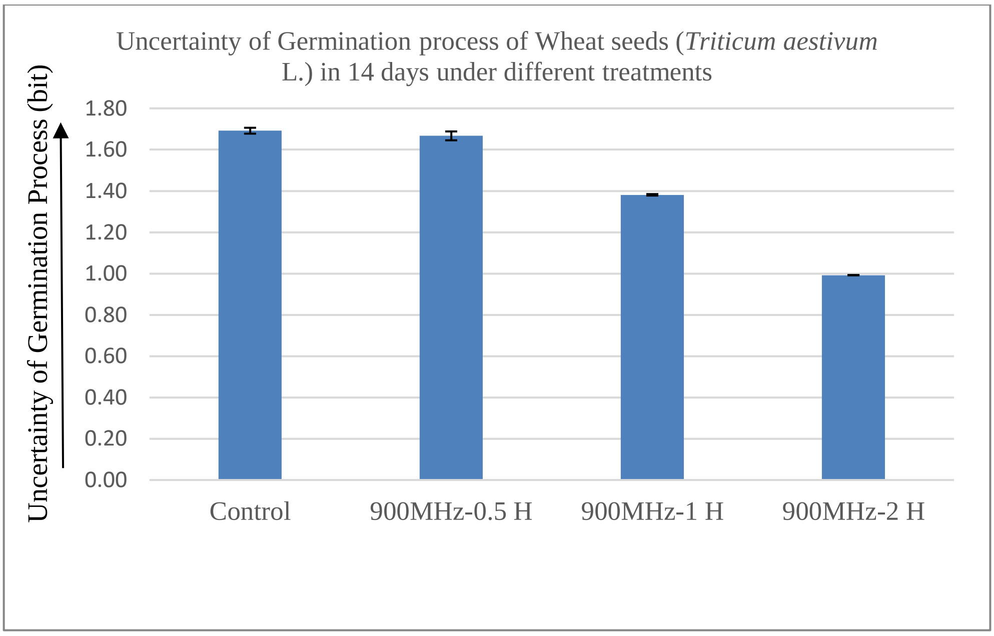

Fig.9: Uncertainty of Germination process of Wheat seeds

The Synchronization Index (Z) is a measure of the degree of synchronization of germination events in a group of seeds. The values of Synchronization Index (Z) increased across the experimental setup with increased exposure duration. (Fig 10). MDG was highest for untreated control seeds (Fig 11) compared to treated seeds. This suggests that the treatment with high frequency EMF has negatively affected the germination rate of the seeds. The peak value of germination, which describes the germination rate of a seed lot and reflects its quality [16], decreases with increasing exposure duration to high-frequency electromagnetic field treatment. The peak value ranged from 11.53 for control seeds (not exposed to the electromagnetic field) to 10.17 for seeds treated for 2 hours (Fig 12). This finding suggested that the high-frequency electromagnetic field treatment has a negative effect on the seed quality, leading to lower-quality seeds that are less likely to germinate successfully.

The Germination Value (GV) is an important parameter that helps to evaluate the germination process of seeds by combining speed and completeness of germination. A higher GV indicates a better germination process, which is desirable for agricultural applications. According to the data, untreated seeds had the highest germination value (63.13) among all experimental conditions, indicating the best germination process. Seeds treated for 0.5 hours had a slightly lower GV of 61.15, while seeds exposed for 2 hours had the lowest germination value (44.31) (Fig 13). This suggests that in this study, untreated seeds or those treated for a shorter duration (0.5 hours) demonstrated better germination performance as compared to seeds exposed to treatment for a longer duration (2 hours).

Table 4- Estimation of Synchronization Index (Z), Mean Daily Germination (MDG), Peak Value of germination (PV) and Germination Value (GV) of different treatments. Different letters (a–c) among the group denote the significant differences between the mean at $p < 0.05$ using one-way analysis of variance (ANOVA), Tukey's HSD comparison test, and Scheffe's test.

Treatment	Synchronization Index (Z)	Mean Daily Germination (MDG) [%]	Peak Value of germination (PV) [day^{-1}]	Germination Value (GV)
Control	0.34 ± 0.00^{b}	5.48 ± 0.00^{a}	11.53 ± 0.08^{ab}	63.13 ± 0.37^{a}
900MHz-0.5 H	0.35 ± 0.01^{b}	5.45 ± 0.01^{a}	11.49 ± 0.01^{a}	61.15 ± 0.62^{a}
900MHz-1 H	0.40 ± 0.00^{ab}	4.93 ± 0.01^{b}	11.40 ± 0.01^{ab}	56.69 ± 0.13^{ab}
900MHz-2 H	0.50 ± 0.00^{a}	4.36 ± 0.01^{c}	10.17 ± 0.01^{b}	44.31 ± 0.12^{b}

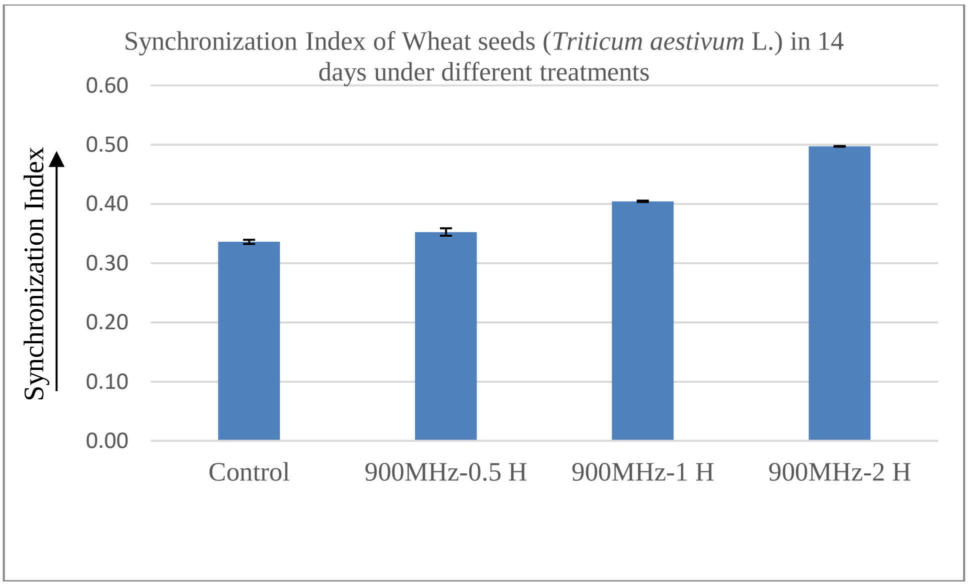

Fig.10 Synchronization Index of Wheat seeds

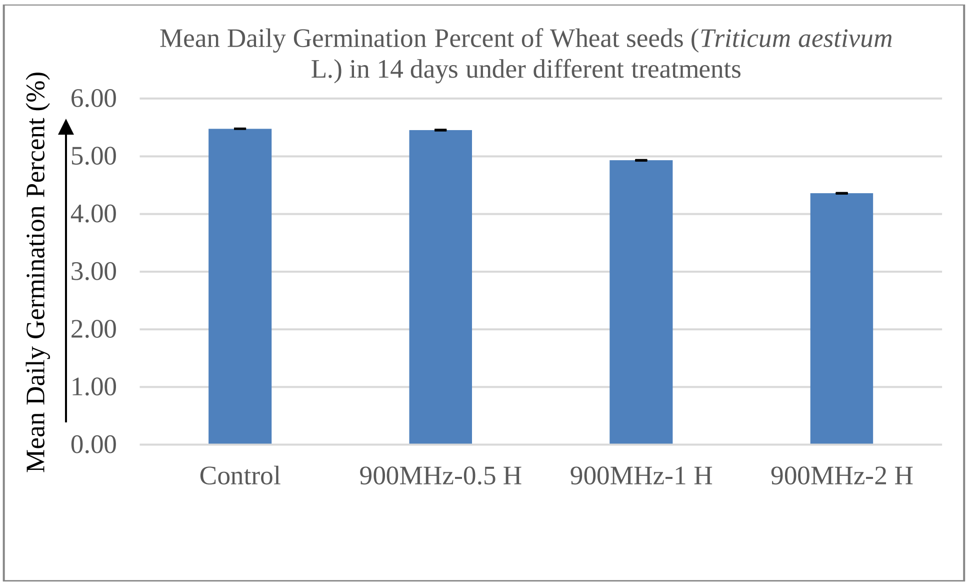

Fig.11 Mean Daily Germination Percent of Wheat seeds

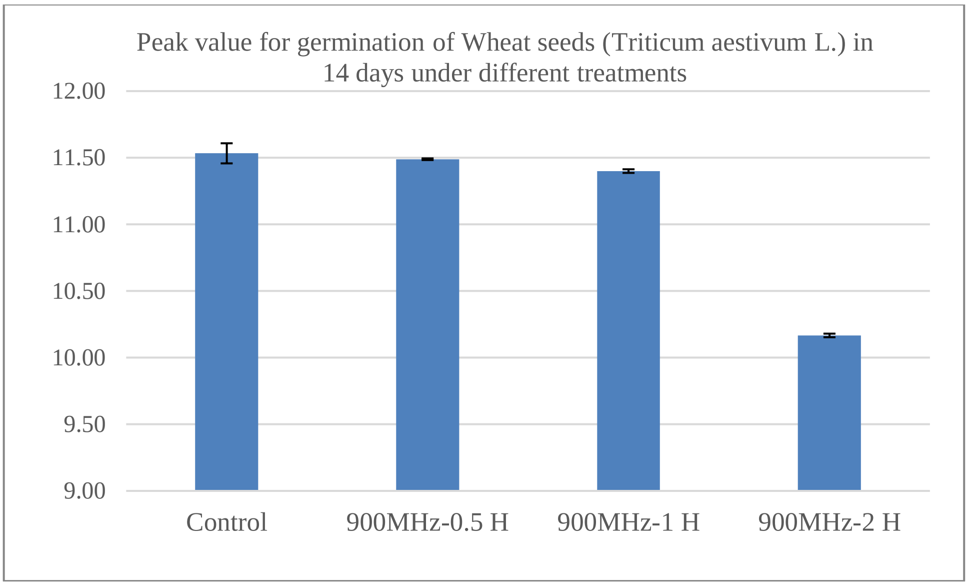

Fig.12 Peak value for germination of Wheat seeds

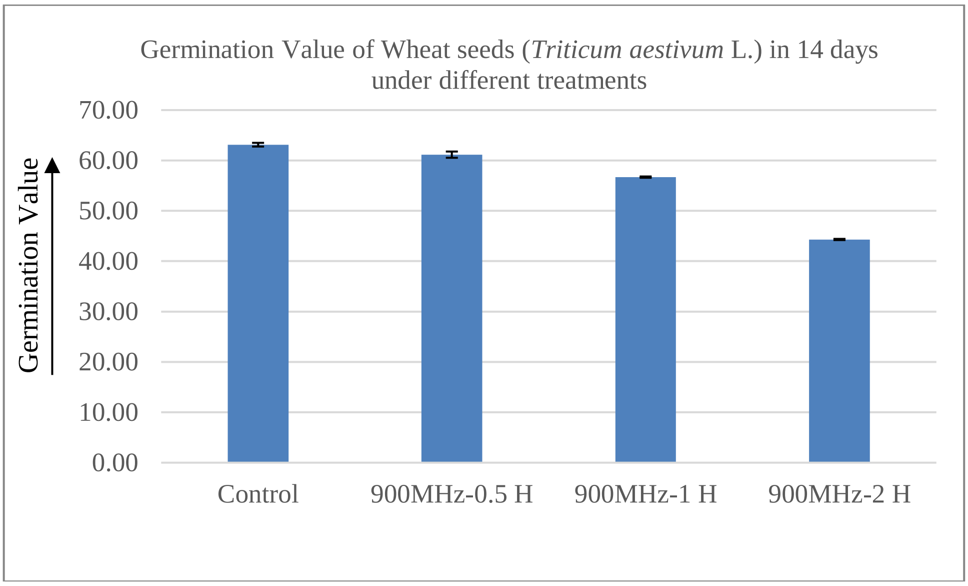

Fig.13 Germination Value for germination of Wheat seeds

IV. CONCLUSION

The results showed that exposure to electromagnetic field radiation (EMF) emitted from cell phones has a negative impact on the germination of wheat seeds in a time-dependent manner. A significant reduction in germination was observed after at least 1 hour of exposure to cell phone EMF. There could be several potential explanations for the observed inhibitory effect of cell phone EMF on wheat germination including cellular damage, oxidative stress and altered gene expression. This study is important in view of the rapid increase in cell phone EMF in the natural environment and its possible impact on natural ecosystem processes and environmental health. It implies a need for environmental risk assessment due to EMF and development of proper management strategies to check EMF pollution in the natural environment. This knowledge can help develop strategies to mitigate the negative effects of EMF on plant germination and growth, which could have implications for agriculture and food security.

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