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MAGNETIC TREATMENT INFLUENCE ON NEXT GENERATION SEEDS OF GREEN GRAM (*Vigna radiata* L.): A COMPARATIVE STUDY

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ABSTRACT
Building on the encouraging results from the initial experiment using magnetic field treatments of different strengths and exposure times for green gram cultivation, treatment T_7 (225 mT for 75 min) was identified as the most effective. To assess its long-term influence, a follow-up trial was carried out during the 2023 kharif season at the farms of Navi Vasni, Aravali, and Gujarat. In this study, green gram (*Vigna radiata*) seeds previously subjected to T_1 (control) and T_7 (225 mT for 75 min) in the first cultivation cycle were reused without additional treatment and designated T_1 (PS) and T_7 (PS), respectively. All treatments, including the untreated seeds, were strewed with a Normal Block Design along with three duplicates, and managed with standard irrigation and vermicompost application. Data on physiological traits, such as sprouting percentage, leaf area, shoot span, root span, and plant height were recorded every 14 days. At harvest, chemical, biochemical, and yield-related parameters, including N, P, K, Fe, Mn, Zn, Cu, chlorophyll a and b, carotenoids, acidity, vitamin C, and seed yield, were evaluated. Comparative scrutiny revealed that seeds from the earlier crop exposed to 225 mT for 75 min [T_7 (PS)] achieved the most favorable outcomes across growth and yield characteristics.

Keywords: *Germination, Physiological Parameters, Chemical Parameters, Biochemical Parameters, Yield*

List of short words
mT – milli Tesla
min – minute
PS – plant seeds
MF – magnetic field

Highlights
- In addition to non-treated seeds T_1 (PS), seeds in the optimal condition T_7 (PS) were planted for further study.
- Various analysis techniques used to determine the results and comparative analyses were performed, as detailed in the paper.
- MF treatment in the initial cropping cycle enhanced the growth, development, and yield of mung beans, and a continuous effect was observed for further cropping cycles.
- The MF treatment also enhanced seed intake intensities when a particular magnetic field was applied, referring to the optimal conditions of initial cropping.

INTRODUCTION
Green gram is considered the foremost pulse crop globally owing to its nutritional, medicinal, industrial, and economic significance. It serves as a vital protein source, especially across Asian countries where it is crucial for a large share of people's protein requirements. Known for being both affordable and easily

available, green gram provides a rich supply of protein and carbohydrates, making it a practical substitute for expensive animal-based proteins and other nutrient sources. Owing to these advantages, crop popularity and consumption have increased substantially over the past ten years.

Green gram is rich in nutrients, oligosaccharides, amino acids, and phenolic compounds, which are believed to be responsible for its antioxidant, anti-inflammatory, antimicrobial, and antitumor properties. These bioactive components are instrumental in regulating lipid metabolism (Randhir *et al.*, 2004; Vanamala *et al.*, 2006; Anjum *et al.*, 2011; Kanatt *et al.*, 2011). Owing to such functional attributes, scientific studies have highlighted the potential of Gram for applications not only in health foods but also in the fields of medicine and cosmetics (Golob, 1999).

Various physical and nonphysical approaches have been employed to enhance plant growth and overall productivity. Among these, exposing seeds to magnetic fields has emerged as an effective method, showing positive effects on plant development. The impact of Earth's GMF on plant growth was first documented in 1862 by French scientist Louis Pasteur. Through his studies on molecular activity and agitation, Pasteur observed that geomagnetic forces beneficially contributed to biological processes in plants.

For many years, researchers have focused on improving seed germination and prolonging seed viability to ensure improved planting outcomes (Kelly and George, 1998). Diverse treatments before planting, such as exposure towards electric and magnetic fields, laser light, and microwave radiation, have been shown to enhance germination efficiency (Pietruszewski and Kania, 2010). Among these, the role of MFs in plant growth has received considerable attention. As early as Savostin (1930) reported, seedlings exposed to magnetic treatment exhibited nearly double the growth rate of untreated seedlings.

Studies conducted on the seedlings of various crops, including beans, corn, wheat, cucumber, rice, and sunflower, have demonstrated that exposure to magnetic fields can significantly promote widening. Early seed treatment with MFs has been shown to improve sprouting percentage, plant vigor, plant extension, and ultimately, crop yield (Alexander and Doijode, 1995; Yinan *et al.*, 2005; Cakmak *et al.*, 2010; Vashisth and Nagarajan, 2010; Shine and Guruprasad, 2012). These findings indicate that seeds and plants respond differently depending on the frequency and intensity of the relevant magnetic field. Thus, the use of MF technology in agriculture presents a promising, eco-friendly, and non-chemical approach to enhance crop productivity while ensuring environmental and user safety.

The present study was designed to explore the residual effects of MF therapy on the subsequent crop generation of green gram, focusing on seed formation, growth, developmental stages, and yield performance under the soil conditions of Navi Vasni, Aravali, and Gujarat, without applying any additional treatment.

MATERIALS AND METHODS

For the subsequent crop cycle, seeds derived from the initial cultivation treatments, namely T_1 (control) and T_7 (exposed to 225 mT for 75 min), were directly utilized as T_1 (PS) and T_7 (PS), respectively, without subjecting them to any additional pre-sowing treatment. This experimental design was intended to assess the carryover effects of MF exposure on seed performance, growth, and yield across successive generations. T_7 was identified as the optimum treatment condition during the first crop cycle, thereby serving as a benchmark for evaluating sustained impacts in the present study.

The selected seeds were subsequently divided into two experimental groups, T_1 (PS) and T_7 (PS). Each treatment consisted of five seeds per replicate, with three replicates maintained to ensure experimental reliability and statistical validity. A comprehensive description of the treatments, along with their particular designations, is presented in Table 1.

Table 1: Experimental treatments

Treatments	Details
T_1 (PS)	Seeds of control plant from initial crop cycle
T_7 (PS)	Seeds of optimal condition (T_7) plant from initial crop cycle

Each treatment contains 3 replications

During the 2023 cropping season, seeds from each treatment were sown in an open-field experiment with three replications following a Normal Block Design. The trial comprised six distinct blocks, each measuring approximately 3 × 3 feet. All agronomic actions were accomplished in accordance with the proposed methods of green gram cultivation, as prescribed by the Ministry of Agriculture, thereby ensuring uniformity and standardization across treatments.
Table 2 provides data on the chemical examination of the experimental soil obtained from laboratory tests.

Table 2: Chemical inspection of the exploratory soil

Components	**Available values**
pH	7.0
carbon (%)	0.39
Nitrogen (kg ha^{-1})	166
Phosphorus (kg ha^{-1})	53
Potassium (kg ha^{-1})	293
Micronutrients	
Cu (mg kg^{-1})	0.64
Fe (mg kg^{-1})	8.22
Mn (mg kg^{-1})	8.1
Zn (mg kg^{-1})	1.18
soluble ions	
SO_4^- (mg kg^{-1})	11.90

During the growth period of green gram, several physiological traits were monitored systematically. The sprouting percentage was recorded 21 days post-sowing (DPS), while variables such as leaf area, root span, shoot span, and plant height were measured at 14-day intervals throughout the crop cycle. Upon completion of the growing season, yield-related attributes, including wet and dry seed mass, and total grain yield, were assessed. Leaf and pod samples were collected for biochemical and nutrient analyses. These included the quantification of green pigments (chlorophyll a, chlorophyll b, and carotenoids), elements and microelements (N, P, K, Fe, Mn, Zn, and Cu), vitamin content, and titratable acidity. All laboratory analyses were performed at Navsari Agricultural University (NAU) using standard analytical protocols.
Data on sprouting percentage, physiological attributes, biochemical and chemical parameters, and yield components were systematically analyzed to evaluate variations and comparative differences among the treatments.

RESULTS

Seed sprouting: In the second cropping cycle, treatment T_7 (PS) exhibited the highest sprouting rate, reaching 93.33% at 21 days post-sowing (DPS), whereas the control treatment T_1 (PS) had a sprouting rate of 73.33% (Figure 1). This represents an improvement of approximately 24% in sprouting percentage under T_7 (PS) compared with T_1 (PS), indicating a significant positive effect of MF treatment on seed sprouting performance.
Vegetative growth: Table 3 summarizes the impact of next-generation MF-treated seeds on vegetative growth characteristics of green gram 70 days post-sowing (DPS). Among the treatments, T_7 (PS) [seeds originating from 225 mT for 75 min exposure, without further treatment] demonstrated superior performance relative to that of the control, T_1 (PS). The results indicated that T_7 (PS) was more effective across many of the evaluated physiological parameters, highlighting its sustained positive influence on vegetative development.

Leaf area

Variations in leaf area were recorded at 14, 28, 42, 56 and 70th day post-sowing (DPS). A marked enhancement was observed in treatment T_7 (PS) from 28 DPS onward, with consistently greater leaf expansion than that of the control throughout the second cropping cycle. At 70 DPS, T_7 (PS) achieved a leaf area of 176.01 cm^2, representing an 8.93% increase over the untreated control T_1 (PS), which recorded 160.96 cm^2. This finding suggests that MF treatment exerted a sustained positive impact on vegetative growth, particularly on leaf development.

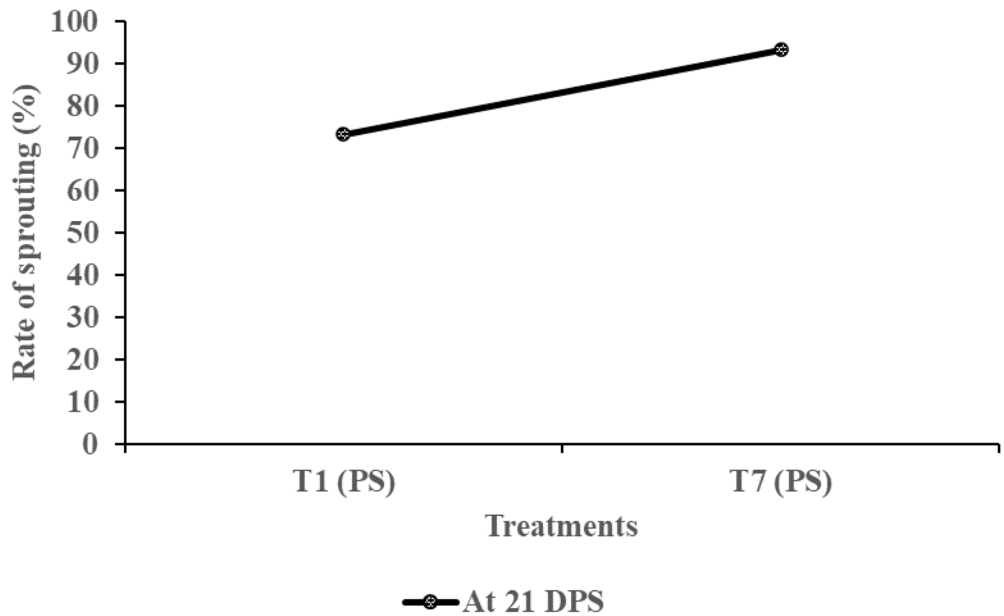

Fig. 1: Effect of next generation seeds on sprouting % rate of green gram seeds at 21 DPS

Shoot span

Shoot span was measured 14, 28, 42, 56, and 70th day post-sowing (DPS). A consistent increase in shoot elongation was observed under treatment T_7 (PS) from 28 DPS onward, during the second cropping cycle. At 70 DPS, plants from T_7 (PS) attained a mean shoot span of 66.80 cm, representing a 6.53% increase over that of the untreated control T_1 (PS), which recorded 62.57 cm. These results indicate that the magnetic field treatment enhanced vegetative growth by promoting shoot development.

Root span

Root span variations were most evident at 42 and 70th day post-sowing (DPS). During the second cropping cycle, treatment T_7 (PS) consistently exhibited superior root development compared with the control. At 70 DPS, T_7 (PS) recorded a mean root span of 22.83 cm, representing a 16.39% increase over that of the untreated control T_1 (PS), which measured 19.37 cm. This detection demonstrated a positive influence of MF treatment on root system enhancement, contributing to the improvement of below-ground growth and potential element intake efficiency.

Plant height

Plant height measurements revealed significant variations 42 and 70th day post-sowing (DPS). During the second cropping cycle, T_7 (PS) consistently outperformed the control in terms of the vertical growth. At 70 DPS, plants from T_7 (PS) achieved a mean height of 89.63 cm, reflecting an 8.97% increase compared with the untreated control T_1 (PS), which measured 81.93 cm. This outcome indicates that residual MF therapy exerted a positive effect on the overall plant stature, potentially contributing to enhanced biomass accumulation.

Table 3: Effect of next generation seeds on vegetative growth of green gram at 70 DPS

Treatments	Average leaf area (cm^2)	Average shoot span (cm)	Average root span (cm)	Average plant height (cm)
T_1 (PS)	160.96	62.57	19.37	81.93
T_7 (PS)	176.01	66.80	22.83	89.63

Values are means of 3 replications

Yield: Table 4 provides a summary of the yield-related traits of green gram observed during the study. Among the treatments, T_7 (PS) [seeds derived from the 225 mT for 75 min exposure in the previous generation, without additional treatment] recorded a markedly higher yield performance compared to the control treatment T_1 (PS).

Wet mass of beans

Among the treatments, T_7 (PS) showed the greatest improvement in biomass accumulation during the second cropping cycle, with a wet mass of 79.93 g. This represented a 12.15% increase compared to that of the untreated control T_1 (PS), which measured 70.77 g. These results indicate that residual MF treatment exerted a favorable influence on plant growth, contributing to enhanced fresh biomass production.

Dry mass of beans

Treatment T_7 (PS) recorded the highest improvement in seed dry mass during the second cropping cycle, reaching a value of 68.07 g. This corresponded to a 12.43% increase over the untreated control T_1 (PS), which registered 60.10 g. This detection identified the sustained positive influence of MF exposure from the previous generation on seed biomass accumulation.

Table 4: Effect of next generation seeds on yield of green gram

Treatments	Average wet mass (g)	Average dry mass (g)
T_1 (PS)	70.77	60.10
T_7 (PS)	79.93	68.07

Values are means of 3 replications

In the second cropping cycle, treatment T_7 (PS) resulted in a substantial improvement in yield, surpassing the average productivity range reported for the Gujarat-4 green gram variety. Specifically, T_7 (PS) achieved a calculated yield of 813.85 kg ha^{-1}, compared to the regional average of 500–700 kg ha^{-1}. This outcome underscores the sustained positive influence of the initial magnetic field treatment, highlighting its potential to enhance yield performance across successive crop generations.

Chemical and biochemical parameters

Leaf biochemical analysis conducted at the end of the cropping cycle revealed notable variations among treatments, with T_7 (PS) [seeds derived from 225 mT for 75 min exposure in the previous generation, without further treatment] exhibiting significantly higher values than the control treatment T_1 (PS).

Chemical parameters

In the second cropping cycle of green gram, treatment T_7 (PS) exhibited a significantly higher leaf nitrogen concentration than the untreated control (T_1). The nitrogen content recorded under T_7 (PS) was 3.32%, reflecting an improvement of 15.93% over that of the control treatment T_1 (PS), which showed a value of 2.83%. This indicates that T_7 (PS) effectively enhanced nitrogen assimilation during the growth period compared with untreated plants. In the second crop cycle, T_7 (PS) exhibited a slight increase in phosphorus concentration compared with T_1 (PS). The phosphorus content in T_7 (PS) was 0.31%, which represented a 3.27% improvement over T_1 (PS) of 0.30%. Although the difference was relatively modest, these findings indicate that T_7 (PS) contributed to a minor enhancement in phosphorus accumulation in green gram leaves during the second cropping season. In terms of potassium content, T_7 (PS) showed a noticeable increase in leaf potassium concentration compared with T_1 (PS). The potassium content in T_7 (PS) was 0.57%, reflecting a 19.23% enhancement over T_1 (PS), which was 0.47%. This outcome suggests that T_7 (PS) positively influenced K accumulation in green gram plants during the second growing season.

Biochemical parameters

During the second cropping cycle, T_7 (PS) exhibited consistently higher concentrations of microelements in green gram leaves than T_1 (PS). For iron, T_7 (PS) recorded 381 ppm, representing a 39.24% increase over T_1 (PS) at 256 ppm. In the case of Mn, T_7 (PS) showed a concentration of 178 ppm, reflecting a 45.51% increase compared to the 112-ppm observed in T_1 (PS). The Zn content followed a similar trend, with T_7 (PS) reaching 41.9 ppm, marking a 22.28% enhancement over T_1 (PS) at 33.5 ppm. Likewise, copper accumulation was the highest under T_7 (PS), with a value of 15.4 ppm, showing a 43.47% increase relative to T_1 (PS), which was 9.9 ppm. The consistent increases in all four microelements under T_7 (PS) suggest that this treatment was more effective in facilitating element accumulation in the plants during the second crop cycle. These results highlight the superiority of T_7 (PS) over T_1 (PS) in terms of microelement enrichment, which may be associated with enhanced physiological processes, root activity, and nutrient mobilization efficiency under field conditions.

In the second cropping cycle, considerable variation was observed in pigment composition among treatments, with T_7 (PS) showing the highest enhancement in chlorophyll a content, whereas T_1 (PS) was associated with comparatively higher chlorophyll b levels. Specifically, T_7 (PS) recorded a chlorophyll a concentration of 0.902 mg g^{-1}, representing a notable improvement over T_1 (PS), which reached 0.577 mg g^{-1} during the same cycle. Relative to the control, T_7 (PS) exhibited a 10.01% increase in chlorophyll a, whereas a marked reduction of 34.75% was observed in chlorophyll b content compared with T_1 (PS). In terms of total chlorophyll concentration, T_7 (PS) displayed a slight decline of 6.29%, valued at 1.308 mg g^{-1} against the control T_1 (PS), which recorded 1.393 mg g^{-1}. In contrast, carotenoid levels showed a strong positive response to T_7 (PS), which reached 0.998 mg g^{-1} during the second cycle, corresponding to a substantial 137.33% increase when compared with T_1 (PS) that contained only 0.185 mg g^{-1}. Overall, the data indicated that T_7 (PS) exerted the most significant influence on photosynthetic pigments, particularly by enhancing chlorophyll and carotenoid contents, whereas chlorophyll b remained comparatively higher in T_1 (PS) (Table 5).

Table 5: Effect of next generation seeds on chemical composition of green gram leaves

Treatments	Total N (%)	Total P (%)	Total K (%)	Fe ppm	Mn ppm	Zn ppm	Cu ppm	Chlorophyll A (mg g^{-1})	Chlorophyll B (mg g^{-1})	Carotenoid (mg g^{-1})
T_1 (PS)	2.83	0.30	0.47	256	112	33.5	9.9	0.816	0.577	0.185
T_7 (PS)	3.32	0.31	0.57	381	178	41.9	15.4	0.902	0.406	0.998

Values are means of three replicates; N: nitrogen, P: Phosphorus, K: Potassium

In the biochemical assessment of beans during the second cropping cycle, most parameters remained relatively consistent across treatments, with only slight variation. Notably, T_1 (PS) resulted in a modest increase in vitamin C concentration, reaching 6.67 mg 100 g^{-1}, which corresponded to a 10.56% rise compared to T_7 (PS), where the value was 6.00 mg 100 g^{-1}. In contrast, T_7 (PS) showed higher acidity than the control treatment. The acidity level under T_7 (PS) was 0.128%, reflecting a 13.33% increase over that under T_1 (PS), which was 0.112%. These findings suggest that while T_1 (PS) favored vitamin C accumulation, T_7 (PS) enhanced acidity levels, indicating differential influences of the treatments on the fruit quality attributes of beans during the second crop cycle (Table -6).

Table 6: Effect of next generation seeds on chemical composition of green gram beans

Treatments	Titratable Acidity (%)	Vitamin C (mg 100 g^{-1})
T_1 (PS)	0.112	6.67
T_7 (PS)	0.128	6.00

Values are means of 3 replications

Element and Microelement intake

During the second crop cycle, T_7 (PS) enhanced element intake more effectively than the control treatment T_1 (PS). In terms of nitrogen assimilation, T_7 (PS) recorded an intake of 27.08 kg ha^{-1}, which represented a 28.46% increase compared to T_1 (PS) with 20.33 kg ha^{-1}. A similar improvement was observed in phosphorus intake, where T_7 (PS) achieved 2.55 kg ha^{-1} > ^{1}, corresponding to a 16.52% rise over T_1 (PS), which was 2.16 kg ha^{-1}. Potassium intake also followed this positive trend, with T_7 (PS) registering 4.67 kg ha^{-1}, reflecting a 31.18% enhancement in comparison to T_1 (PS), which recorded 3.41 kg ha^{-1}. These results clearly demonstrate that T_7 (PS) promoted a greater intake of essential elements, such as nitrogen, phosphorus, and potassium. This supports the improved nutrient acquisition efficiency in the green gram during the second cropping season.

In the second crop cycle, T_7 (PS) consistently exhibited superior microelement intake compared to the control treatment T_1 (PS). Iron intake under T_7 (PS) was 310.71 g ha < $^{-1}$ > ^{1}, reflecting a 51.10% increase over T_1 (PS), which recorded 184.23 g ha^{-1}. A similar trend was observed for manganese, where T_7 (PS) achieved an intake of 145.18 g ha^{-1}, corresponding to a 56.93% rise compared with T_1 (PS) at 80.84 g ha^{-1}. Zinc intake was also enhanced under T_7 (PS), with a value of 34.30 g ha^{-1}, representing a 34.93% improvement relative to T_1 (PS), which recorded 24.10 g ha^{-1}. Furthermore, copper intake reached its maximum under T_7 (PS), with 12.61 g ha^{-1}, indicating a 54.74% increase in comparison to T_1 (PS) at 7.19 g ha^{-1}. Collectively, these results highlight the strong influence of T_7 (PS) in promoting the intake of essential microelements such as iron, manganese, zinc, and copper. This underscores its effectiveness in improving nutrient acquisition and the overall mineral nutrition of green gram during the second growing season (Table 7).

Table 7: Effect of next generation seeds on element and microelement intake of green gram plant

Treatments	N intake (kg ha^{-1})	P intake (kg ha^{-1})	K intake (kg ha^{-1})	Fe intake (g ha^{-1})	Mn intake (g ha^{-1})	Zn intake (g ha^{-1})	Cu intake (g ha^{-1})
T_1 (PS)	20.33	2.16	3.41	184.23	80.84	24.10	7.19
T_7 (PS)	27.08	2.55	4.67	310.71	145.18	34.30	12.61

Values are means of three replicates; N: nitrogen, P: Phosphorus, K: Potassium

DISCUSSION

These results indicate that exposure to electromagnetic fields exerts a positive effect on plant metabolic processes. Improvements have been observed in several growth parameters, including germination rate, leaf expansion, shoot and root elongation, and overall plant height under magnetic field treatments. This suggests that, before planting, magnetic conditioning of ovules may enhance photosynthetic carbon assimilation, thereby contributing to greater biomass accumulation (Joshi *et al.*, 2014). Similar outcomes have been documented across different crop species, such as soybean (Shine *et al.*, 2011a), maize (Shine and Guruprasad, 2012), cucumber (Bhardwaj *et al.*, 2012), cotton (Bilalis *et al.*, 2011), sunflower (Vashisth and Nagarajan, 2010) and chickpea (Vashisth and Nagarajan, 2008), and notable improvements in the germination rate and speed have been consistently reported.

As shown in Fig. 1, the sprouting rate exhibited a marked increase after treatment with T_7 (PS). Previous studies have demonstrated that MF exposure enhances seed sprouting, accelerates early growth, promotes protein synthesis, and stimulates root development (Aladjadjiyan, 2002; Atak *et al.*, 2003). Martinez *et al.* (2017) further reported that external magnetic fields can improve the seed vigor index by impacting metabolic processes, particularly through the activation of enzymes and associated proteins. Radhakrishnan (2018, 2019) suggested that magnetic field treatments improve seed standards by balancing the metabolism of reserve proteins and dietary fat, thereby enhancing plant growth, physiological performance, and resilience to environmental stress factors.

In the second crop cycle, the root span in T_7 (PS) was considerably greater than that in T_1 (PS), as presented in Table 3. Treatment T_7 (PS) resulted in a 16.39% increase over T_1 (PS), indicating a clear improvement in root development. This enhancement suggests that magnetic treatment positively influences water absorption by embryonic tissues during the early physical germination phase. Enhanced water intake likely promoted higher cellular turgor pressure in the radicle, thereby facilitating stronger root elongation in seedlings derived from magnetically treated seeds.

Leaf chemical and biochemical analyses during the second cropping cycle revealed that T_7 (PS) resulted in increased immersion in elements such as nitrogen (N%), phosphorus (P%), and potassium (K%), along with a marked enhancement in the microelement levels of iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu). The constructive consequence of MF treatment is believed to stem from the activation of bioenergetic systems within plant cells, which in turn stimulate membrane transport processes and enzymatic activities. Such influences may alter the dynamics of key biochemical mechanisms, including ATP hydrolysis, and potentially modify the structural conformation of essential proteins, thereby contributing to improved nutrient assimilation and metabolic efficiency (De Souza *et al.*, 2005).

The marked improvement in vegetative development indicators, including leaf area, shoot span, root span, and overall plant height, under T_7 (PS) can be linked to the elevated concentrations of photosynthetic pigments, particularly carotenoids, along with chlorophyll a and b (Table 5). The increase in these pigment levels likely enhanced the light absorption capacity, thereby supporting greater photosynthetic activity and improved vegetative performance in the treated plants. Consistent with these findings, earlier studies have shown that MF exposure enhances photochemical reactions within chlorophyll molecules, leading to higher green pigment accumulation in crops, such as wheat and beans (Lebedev *et al.*, 1977). Similarly, Saktheeswari and Subrahmanyam (1989) observed increased chlorophyll content and a reduction in chloride deficiency when rice ovules were subjected towards oscillating MF treatment.

In a comparative study, T_7 (PS) demonstrated markedly higher absorption of elements such as nitrogen, phosphorus, and potassium, along with microelements, including iron, manganese, zinc, and copper, when compared to the control treatment T_1 (PS). This enhanced nutrient intake might be associated with the superior root characteristics observed in T_7 (PS). Supporting evidence from earlier studies indicated that magnetic field exposure plays a crucial role in improving root traits. Vashisth and Nagarajan (2010) reported a substantial increase in root span and effective root area in sunflower seedlings endured towards direct current MF varying from 0 to 250 mT. Similarly, Muraji *et al.* (1998) found that maize seedlings exposed to AC magnetic fields of 10 and 20 Hz exhibited approximately 20% more root expansion compared to untreated controls. As root span and effective plane are critical physiological variables for evaluating nutrient intake efficiency, as emphasized by Wang *et al.* (2006), the results of this study suggest that T_7 (PS) promotes root system development, thereby facilitating greater mineral acquisition in the second crop cycle.

The implementation of MF therapy in an earlier crop cycle produced favourable outcomes in both wet and dry mass of beans during the second cropping cycle, as presented in Table 4. Notably, the yield improvement observed under T_7 (PS), together with the increased vitamin C concentration reported in Table 6, can be largely attributed to an enhancement in the average bean weight under this treatment. The observed increase in growth and biomass accretion may be linked to more efficient light capture and a reduction in free radical damage in plants derived from magnetically treated seeds, resulting in lower levels of reactive oxygen species. Furthermore, these treatments appeared to promote nutrient intake, which in turn likely enhanced photosynthetic efficiency. The additional carbon fixed through this process was redirected toward biomass production, ultimately contributing to higher yields of green grams.

CONCLUSIONS

The results demonstrate that the implementation of seed MF treatment during the initial crop cycle also exerts a positive influence on the second cropping cycle. In this phase, T_7 (PS) (non-treated seeds exposed to 225 mT for 75 min) emerged as the most effective treatment, showing consistent improvements across multiple parameters compared with T_1 (PS). Specifically, T_7 (PS) contributed to higher sprouting percentages, enhanced vegetative growth, better developmental traits, and improved yield performance in green gram. A key outcome of this research is that MF treatment applied at the seed stage not only produced immediate benefits in the first crop cycle but also continued to impart significant advantages in the subsequent cycle. Moreover, these findings emphasize that specific magnetic field intensities can improve seed quality traits. Importantly, the use of magnetic fields as seed treatment offers an environmentally sustainable alternative to conventional chemical and biological approaches, thereby presenting a promising eco-friendly strategy for crop improvement.

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