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The Impact of Static Magnetic Fields on the Quality of Forage Pea: A Multidimensional Assessment

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HIGHLIGHTS

- Static magnetic fields induced notable changes in the physiological performance and forage quality traits of pea seedlings.
- Moderate-intensity magnetic fields (especially 0.7 T) enhanced plant stress tolerance by triggering both enzymatic and metabolic defense systems, while also optimizing parameters that determine forage quality, such as phenolic and protein content.
- The high SMF intensity (1.1 T) caused a decrease in some parameters (e.g., enzyme activities), indicating a possible "overstimulation" effect.
- The results suggest that SMF applications can have either positive or negative impacts on plant performance depending on the dose, highlighting the critical importance of determining the optimal MF level for agricultural practices

Abstract

This study aimed to evaluate the effects of static magnetic fields of varying intensities (0, 0.5, 0.7, 0.9, and 1.1 Tesla) applied to forage pea (*Pisum sativum ssp. arvense* L.) seeds on physiological parameters, antioxidant defense systems, and forage quality. The magnetic field treatments were applied to the seeds for 10 minutes, after which the seeds were grown under controlled climate conditions for 28 days. In addition to physiological parameters such as chlorophyll and carotenoid content, various biochemical parameters including MDA, proline, SOD, CAT, and APX were assessed, along with total phenolic compounds, flavonoids, tannins, DPPH radical scavenging capacity, crude protein content, ADF, NDF, and nutrient composition (K, Ca, Mg, P). According to the results, especially the 0.7 T and 0.9 T SMFtreatments led to increases in chlorophyll b and total chlorophyll content and had regulatory effects on proline and MDA levels. At the same doses, significant increases were observed in total phenolic content, flavonoid levels, and antioxidant enzyme activities. PCA and heatmap analyses further supported that these treatments positively influenced key determinants of forage quality. In conclusion, moderate-intensity SMFtreatments improved physiological and biochemical processes in forage pea seedlings, promoted secondary metabolite production, and enhanced overall forage quality. In this context, magneto-priming emerges as a sustainable and environmentally friendly agricultural enhancement method.

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1. Introduction

The quality of plants in agricultural production is primarily proportional to the initial seed quality. The physical, chemical, and biochemical characteristics of seeds play a decisive role in plant development starting from germination, ultimately reflecting on the quality of the final product. In this context, seed priming through magnetic field (MF) applications stands out as an effective method to enhance seed quality. Magnetic field priming stimulates metabolic activities by enabling more efficient utilization of water and nutrients in seed tissues, thereby supporting optimal levels of key biochemical processes such as germination rate, energy transfer, and antibiotic enzyme activities (Maheshwari and Grewal, 2009). Additionally, MF applications strengthen the internal antioxidant systems of seeds, minimize the effects of oxidative stress, and mitigate cellular damage (Atak et al., 2003). This contributes to improved germination potential and seedling vigor, ultimately resulting in healthier and more resilient plants during later growth stages. Consequently, enhancing seed quality leads to better adaptability and productivity throughout the plant's life cycle, underlining the significance of MF priming in sustainable agriculture and high-quality crop production. In this regard, magnetic field applications are considered an environmentally friendly approach due to their positive impacts on seed germination, seedling development, and biochemical structure (Florez et al., 2007).

The effects of magnetic fields on plants vary depending on the intensity and duration of the application, plant species, and developmental stage. Previous studies have reported that MF treatments increase germination rates, improve chlorophyll and carotenoid levels, activate antioxidant defense systems, and induce significant changes in plant metabolism (Vashisth and Nagarajan, 2010; Martínez et al., 2002). Notably, the increased activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) suggests that MF may play a role in managing oxidative stress (Dardeniz and Yalçınkaya, 2012).

The impact of magnetic fields on plants depends on multiple factors, including the magnetic field intensity (expressed in Tesla or mT), duration of exposure, plant species, seed physiological status, and developmental phase. The literature presents numerous findings showing that MF treatments can increase germination speed and rate, enhance morphological traits such as root and shoot length, support the preservation of photosynthetic pigments, and modulate cellular metabolism (Martínez et al., 2002; Radhakrishnan & Kumari, 2013). MF has also been shown to improve chlorophyll and carotenoid content and activate antioxidant defense systems (Vashisth and Nagarajan, 2010). In particular, low-intensity magnetic fields (0.1–1.1 T) have been reported to stimulate seed metabolism, support early seedling development, and maintain embryo viability (Esitken & Turan, 2004). One of the most remarkable effects of MF is the activation of enzymatic defense systems involved in combating oxidative stress. Increased activities of SOD, CAT, and APX indicate that magnetic fields may directly or indirectly contribute to detoxifying reactive oxygen species (ROS) (Dardeniz & Yalçınkaya, 2012; Tkalec et al., 2009). For example, Atak et al. (2007) reported that MF application in maize (*Zea mays*) seeds reduced lipid peroxidation, preserved membrane integrity, and increased total soluble protein levels. Similarly, Florez et al. (2007) demonstrated the positive effects of MF on germination rates and chlorophyll content in linseed seeds. Another study reported that exposing barley seeds to MF increased their water uptake capacity, shortened germination duration, and activated mitochondrial enzymes involved in ATP synthesis (Iqbal et al., 2012). These findings support the hypothesis that magnetic fields can enhance metabolic activation by affecting ion

fluxes and the electrical potential of cell membranes. Therefore, magnetic fields applied at appropriate intensities and durations may support physiological activation of seeds, promote post-germination growth, and contribute to improved resistance of plants against environmental stress conditions. However, since the effects of MF applications may vary by plant species and environmental factors, it is essential to determine optimized parameters for each species.

Among forage crops, forage pea (*Pisum sativum* subsp. *arvense*) holds significant value in animal production due to its high crude protein content, digestibility, and biological value (Karkanis et al., 2016; Sipahioğlu et al., 2022; Mirza and Doğrusöz, 2023). However, studies involving MF applications on this species remain quite limited. Therefore, elucidating the effects of various SMF intensities applied to forage pea seeds on physiological, biochemical, and nutritional traits will provide valuable insights for both plant biotechnology and animal nutrition. In this context, the present study aims to investigate, for the first time in a comprehensive manner, the potential effects of magneto-priming on growth, metabolic responses, and forage quality in forage pea.

2. Materials and Methods

Plant Material and Experimental Conditions

In this study, forage pea (*Pisum sativum ssp. arvense* L.) seeds were used as the plant material. Prior to treatment, seeds were screened for foreign materials and physical damage, and only healthy individuals were selected. The experiments were conducted under controlled conditions in the climate chamber of the Faculty of Agriculture at Yozgat Bozok University (YOBU). The chamber was maintained at a temperature of 25 ± 2 °C, relative humidity of 60–70%, and a photoperiod of 16 hours light / 8 hours dark.

The forage pea seeds were exposed to five different static SMF intensities—0 (control), 0.5, 0.7, 0.9, and 1.1 Tesla (T)—for 10 minutes using a Hall Effect Measurement System (HEMS). Immediately after the SMF treatment, seeds were sown without delay into pots measuring 17 × 50 × 15 cm, using a completely randomized design with three replications. Each pot contained a sterilized peat:perlite mixture (1:1), and 10 plants were established per pot. Each pot was considered one replication. Plants were grown under well-watered conditions for the first 20 days, followed by 8 days of progressive drought stress by withholding water (Doğrusöz et al., 2024). On day 28, the seedlings were harvested, and 8 grams of fresh leaf tissue from each pot were collected and stored at −20 °C for subsequent analyses. All biochemical analyses were carried out in triplicate.

Physiological Measurements

Fresh leaf samples that had been preserved were used to determine chlorophyll a, chlorophyll b, and total chlorophyll contents spectrophotometrically, according to the method described by Witham et al. (1971). Carotenoid content was analyzed following the procedure outlined by Kirk and Allen (1965). The formulas used in the calculations are provided below.

$$Chl\ a\ (mg\ g^{-1}) = 12.7x(A663\text{-}2.69)xA645\ x\ V/1000xW$$

$$Chl\ b\ (mg\ g^{-1}) = 22.91x(A645\text{-}4.68)xA663\ x\ V/1000xW$$

$$Total\ chl\ (mg\ g^{-1}) = chl\ a + chl\ b$$

$$\text{Carotenoids (mg g}^{-1}) = A480 + (0.114 \times A663 - 0.638 \times A645$$

(V:extract volume (mL), W:leaf fresh weight (g),A: absorbance in the specified wavelength)

Biochemical Analyses

The content of malondialdehyde (MDA, nmol g^{-1}), an indicator of lipid peroxidation, was determined using the thiobarbituric acid reactive substances (TBARS) method described by Zhang et al. (2007). The

amount of proline (μmol g^{-1}), which indicates osmotic stress, was measured colorimetrically with ninhydrin following the method of Bates et al. (1973).

The activities of antioxidant enzymes including superoxide dismutase (SOD; U mg^{-1} protein), catalase (CAT; μmol mg^{-1} protein), and ascorbate peroxidase (APX; μmol mg^{-1} protein) were determined according to the methods of Gong et al. (2005), Aebi (1984), and Nakano & Asada (1981), respectively.

Parameters Related to Forage Quality

Phenolic Compounds and Flavonoids: Total phenolic compounds (mg GAE g^{-1}) were measured using the Folin–Ciocalteu reagent, and the results were expressed as gallic acid equivalents (GAE) (Singleton et al., 1999). Total flavonoid content (mg QE g^{-1}) was determined using the aluminum chloride method (Arvouet-Grand et al., 1994). DPPH (2,2-diphenyl-1-picrylhydrazyl; %) radical scavenging activity was measured spectrophotometrically according to the method of Brand-Williams et al. (1995). Condensed tannins (%) were determined by the Vanillin-HCl method (Bate-Smith, 1975).

All remaining seedlings in each pot were harvested to analyze crude protein, acid detergent fiber (ADF), neutral detergent fiber (NDF), and mineral contents. The samples were oven-dried at 65 °C, ground to a fine powder, and analyzed using a NIRS device with the IC-0904-FE calibration program. Results were expressed as percentages.

Statistical Analysis

The data obtained were evaluated by one-way analysis of variance (ANOVA), and significant differences among means were determined using a multiple comparison test in SPSS 20.0 software ($p < 0.05$).

3. Results and Discussion

The effects of different SMF treatments on the evaluated parameters in forage pea seedlings are presented in detail in Tables 1, 2, and 3.

Table 1. Effect of different static magnetic field intensities on chlorophyll, carotenoid, MDA and proline content in forage pea seedlings.

Magnetic Field	Chl a mg g-1	Chl b mg g-1**	Chl a+b mg g-1**	Carotenoid mg g-1**	MDA nmol g-1	Prolin μmol g-1**
0 T	61.66	67.41 c	129.06 d	0.809 c	1.59	2.33 a
0.5 T	58.59	92.17 b	150.76 b	0.615 c	1.55	1.86 b
0.7 T	61.71	96.86 a	158.58 a	0.435 c	1.77	1.75 b
0.9 T	61.89	98.23 a	160.12 a	3.459 a	1.65	1.86 b
1.1 T	61.07	71.60 b	132.68 c	2.453 b	1.54	1.49 c
Mean	60.99	85.25	146.24	1.555	1.62	1.86

Values represent the mean of three replicates. Different letters in the same column indicate significant differences ($p < 0.05$);* *:$p<0.01$.

Firstly, the chlorophyll a (Chl a) content remained at similar levels to the control (0 T) in all SMF treatments, with no significant changes observed (average ~61 mg g^{-1}). However, notable increases were detected in chlorophyll b (Chl b) and total chlorophyll (Chl a+b) contents. In particular, under 0.7 T and 0.9 T SMF intensities, Chl b levels were found to be considerably higher than the control (67.41 mg g^{-1}), reaching 96.86 and 98.23 mg g^{-1}, respectively (Table 1). Similarly, total chlorophyll content increased significantly in the same two groups, recorded as 158.58 and 160.12 mg g^{-1}. These findings indicate that SMF treatment particularly stimulates the synthesis of chlorophyll b, thereby enhancing the overall density of photosynthetic pigments. Similar outcomes were reported by Martínez et al. (2002) and Vashisth & Nagarajan (2010), where SMF applications increased chlorophyll content in plants.Carotenoid content varied depending on the intensity of the applied magnetic field. In the control and low SMF groups (0.5 T and 0.7 T), carotenoid levels were low and similar (0.43–0.81 mg g^{-1}), while significant increases were observed under 0.9 T and 1.1 T treatments (3.46 and 2.45 mg g^{-1}, respectively). Considering the protective role of carotenoids against oxidative stress (Demmig-Adams & Adams, 1996; Vashisth & Nagarajan, 2010), these increases suggest that SMF may trigger defense mechanisms in the plant to cope with oxidative stress.

Malondialdehyde (MDA) content is used as an indicator of lipid peroxidation in cell membranes (Heath & Packer, 1968). According to the table, MDA levels did not differ significantly between SMF treatments and the control (average 1.54–1.77 nmol g^{-1}), indicating that SMF application did not markedly increase lipid peroxidation or that it may have limited damaging oxidative stress(Table 1).Proline content, known for its role in stress response and osmoprotection (Bates et al., 1973), showed a distinct decrease under SMF treatments. While the highest proline content (2.33 μmol g^{-1}) was recorded in the control group, it significantly decreased under SMF treatments. Notably, under the 1.1 T application, the proline level dropped significantly to 1.49 μmol g^{-1}. This suggests that the SMF reduced stress levels in the plant, lowering proline accumulation and enhancing stress tolerance (Maheshwari & Grewal, 2009).In conclusion, this study demonstrates that SMF treatment in forage pea seedlings led to increases in photosynthetic pigments, particularly chlorophyll b and total chlorophyll, carotenoid levels depending on SMF intensity, and favorable regulation of stress markers. These findings are consistent with the literature and support the idea that SMF application is a potential biostimulant that can enhance plant growth and stress tolerance (Florez et al., 2007; Martínez et al., 2002).

Table 2. Effect of different static magnetic field intensities on enzymes, DPPH and T. phenolic, T. flavonoid and condensed tannin content in forage pea seedlings.

Magnetic Field	SOD Umg^{-1} protein**	CAT $\mu mol.mg^{-1}$ protein **	APX $\mu mol.mg^{-1}$ protein	T. phenolic *mg GA g^{-1}***	DPPH %	T. flavonoid *mg QE g^{-1}***	Condensed Tannin %**
0	31.12 a	0.21 a	2.43	91.24 c	62.19	1.42 ab	2.12 c
0.5	31.70 a	0.01 b	2.07	108.54 a	58.64	1.29 b	1.93 d
0.7	30.53 a	0.05 b	2.02	111.38 a	59.18	1.54 a	1.91 d
0.9	26.31 ab	0.04 b	2.07	107.86 a	62.57	1.42 ab	2.51 a
1.1	21.27 b	0.06 b	1.48	102.05 b	61.68	1.42 ab	2.32 b
Mean	28.19	0.07	2.02	104.22	60.85	1.42	2.16

Values represent the mean of three replicates. Different letters in the same column indicate significant differences ($p < 0.05$); **:$p<0.01$.

Based on the table data, the effects of different SMF intensities on antioxidant enzyme activities, total phenolic compounds, antioxidant capacity, as well as flavonoid and tannin contents were evaluated in forage pea seedlings (Table 2). The effects of SMF applications on antioxidant defense systems play a key role in enhancing plant resilience to environmental stress conditions.SOD activity was highest in the control group (0 T) at 31.12 U mg^{-1} protein and maintained similar levels in the 0.5 T and 0.7 T treatments. However, significant decreases in SOD activity were observed at 0.9 T and especially at 1.1 T SMF intensities. The SOD enzyme plays a critical role in detoxifying reactive oxygen species (ROS) in plants (Beauchamp & Fridovich, 1971). The reduction of SOD activity at higher SMF intensities may indicate a shift in ROS balance or the activation of alternative antioxidant mechanisms. Additionally, moderate magnetic fields have been shown to enhance the breakdown capacity of reactive oxygen species (ROS) (Kthiri et al., 2024). CAT activity was highest in the control group (0.21 μmol mg^{-1} protein) and significantly decreased across all SMF treatments (0.01–0.06 μmol mg^{-1} protein). Catalase plays an important role in the decomposition of hydrogen peroxide (Aebi, 1984). The decrease in CAT activity following SMF application could be interpreted as suppression of enzyme activity or a reduction in protein synthesis. APX activities varied between 1.48 and 2.43 μmol mg^{-1} protein depending on the SMF intensity, but no significant differences were detected. APX reduces hydrogen peroxide via ascorbate in plant cells and is an important component of antioxidant defense (Nakano & Asada, 1981). Conservation of APX activity was noted at 0.5 T and 0.9 T, while the lowest level was recorded at 1.1 T. This suggests that high magnetic fields may suppress the antioxidant defense system after exceeding a certain threshold (De Souza et al., 2014). Total phenolic compounds increased significantly with SMF application; phenolic content in the 0.5, 0.7, and 0.9 T groups was measured above the control level (91.24 mg GAE g^{-1}). Phenolic compounds are bioactive metabolites that play an important role in the plant antioxidant defense system (Singleton et al., 1999). This increase indicates that SMF enhances stress tolerance and antioxidant capacity in plants. DPPH radical scavenging activity was similar across all groups (average 60.85%) with no significant change, although the highest value (62.57%) was recorded at 0.9 T. This shows that antioxidant defense is supported not only enzymatically but also by metabolites such as phenolic compounds. Total flavonoid content reached its highest value (1.54 mg QE g^{-1}) at 0.7 T, though no significant

differences were observed among other groups. Flavonoids, a subclass of phenolic compounds, play a role in plant stress responses (Harborne & Williams, 2000). Concentrated tannin content was highest at 0.9 T (2.51%) with significant differences compared to control (2.12%) and other treatments. Tannins are polyphenolic compounds involved in plant defense mechanisms and antioxidant protection (Price et al., 1978). Overall, SMFapplications led to decreases in antioxidant enzyme activities in forage pea while increasing total phenolic compounds and certain phenolic subclasses. This suggests that SMF activates non-enzymatic antioxidant pathways in the oxidative stress response and diversifies plant stress tolerance mechanisms. Similarly, modulatory effects of SMF treatments on plant antioxidant components reported by Florez et al. (2007) and Maheshwari & Grewal (2009) are consistent with these findings.

Table 3. Effect of different Static magnetic field intensities on crude protein, ADF, NDF and mineral matters content in forage pea seedlings.

Magnetic Field	ADF %**	NDF %**	CA %**	K %**	MG %**	P %**	Crude protein %**
0	11.36 c	20.74 d	1.66 d	3.67 b	0.47 e	0.42 c	30.94 d
0.5	14.56 a	24.97 b	1.77 c	3.52 c	0.51 c	0.41 e	31.48 cd
0.7	11.32 c	21.45 d	1.86 b	3.41 d	0.49 d	0.45 b	32.03 bc
0.9	14.79 a	26.73 a	1.93 a	3.99 a	0.52 b	0.42 d	32.66 b
1.1	13.27 b	23.69 c	1.94 a	3.62 b	0.53 a	0.46 a	33.58 a
Mean	13.06	23.52	1.83	3.64	0.50	0.43	32.14

Values represent the mean of three replicates. Different letters in the same column indicate significant differences ($p < 0.05$); **:$p<0.01$.

Acid detergent fiber (ADF) and neutral detergent fiber (NDF) are the main structural carbohydrates that influence forage digestibility. ADF includes lignin and cellulose, while NDF encompasses a broader range of fiber components, including hemicellulose. In the control group, ADF and NDF values were at their lowest levels, measured at 11.36% and 20.74%, respectively (Table 3). Particularly in the 0.5 T and 0.9 T treatments, these values increased significantly (ADF: 14.56% and 14.79%; NDF: 24.97% and 26.73%), indicating an elevation in forage fiber content. This suggests that SMF application at certain intensities may stimulate the synthesis of cell wall components (Atak et al., 2003). However, the decrease in ADF and NDF levels under the intermediate intensity of 0.7 T implies that the effect of SMF varies depending on the dosage.Crude ash (CA) represents the total inorganic (mineral) content in forage crops. As SMF intensity increased, CA content also rose, reaching the highest levels (1.93–1.94%) under the 0.9 T and 1.1 T treatments. This indicates that SMF application may have a positive impact on mineral uptake and transport. Similarly, potassium (K), magnesium (Mg), and phosphorus (P) contents also responded to SMF treatments. The highest K (3.99%) and Mg (0.53%) levels were observed under 0.9 T and 1.1 T, while the highest phosphorus content (0.46%) was found at 1.1 T. Potassium and magnesium play key roles in plant metabolism and protein synthesis, while phosphorus is critical for energy metabolism and cellular structure (Marschner, 1995). These findings suggest that SMF enhances nutrient accumulation in plants by promoting ion transport (Florez et al., 2007).Crude protein content is one of the most important criteria directly affecting forage quality. SMF treatments led to significant increases in crude protein content compared to the control group. The highest protein content (33.58%) was obtained under the 1.1 T treatment. This result highlights the stimulatory effect of SMF on protein synthesis. Similarly, previous studies have shown that SMF applications increase amino acid accumulation and accelerate nitrogen metabolism in plants (Cakmak et al., 2010; Maheshwari & Grewal, 2009). In this context, higher SMF intensities such as 0.9 T and 1.1 T appear to be particularly effective in enhancing forage quality.These results clearly demonstrate that SMF application improves the nutritional quality of forage pea seedlings. Especially at higher intensities (0.9–1.1 T), SMF leads to improved forage value through increased protein content, enhanced mineral accumulation, and a balanced fiber composition. These findings indicate that SMF applications can offer significant benefits not only in supporting plant growth but also in improving agricultural quality parameters.

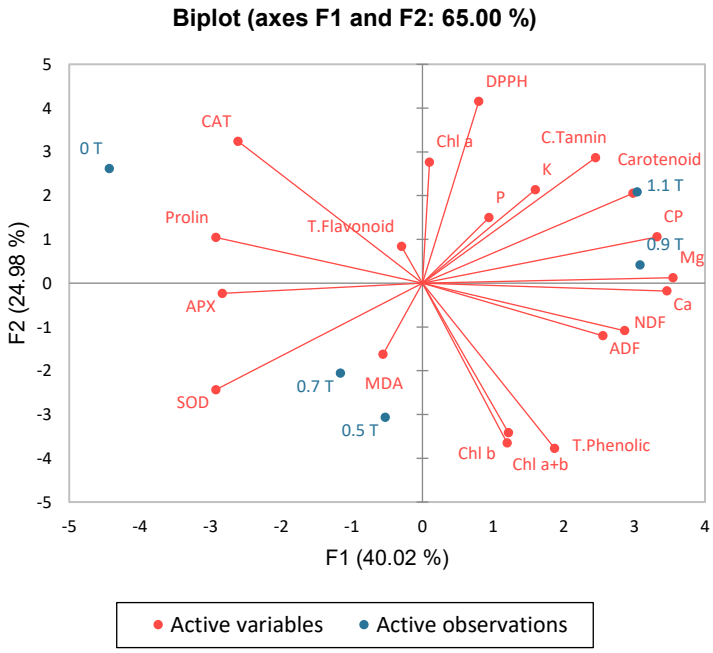

Figure 1. Principal Component Analysis of all examined parameters in different static magnetic field intensities

In this study, the effects of different SMF intensities on the physiological, biochemical, and forage quality traits of forage pea seedlings were evaluated multidimensionally through Principal Component Analysis (PCA) and heatmap analyses. The results clearly demonstrate that SMF applications induce dose-dependent effects and activate distinct mechanisms in plant metabolism.

The PCA biplot analysis, explaining 65% of the total variance (F1: 40.02%, F2: 24.98%), served as a powerful tool to understand the relationship between SMF treatments and plant responses (Figure 1). In the biplot, the 0.9 T and 1.1 T groups clustered closely with chlorophyll a, carotenoids, total protein, macronutrients (Ca, K, Mg, P), and secondary metabolites (DPPH, tannins), indicating that high-intensity SMF treatments enhance biosynthetic activity and improve forage quality. This finding aligns with Shine et al. (2011) and Anand et al. (2012), who reported that SMF promotes mineral uptake and protein synthesis by increasing cell membrane permeability. On the other hand, the 0.5 T and 0.7 T groups showed high correlations with antioxidant defense enzymes (SOD, CAT, APX) and proline, suggesting that these treatments primarily modulate oxidative stress responses. This observation is consistent with the findings of Radhakrishnan and Kumari (2013), who noted that low-intensity SMF treatments enhance stress tolerance by inducing antioxidant systems. Additionally, the 0 T (control) group positioned independently in the negative direction of the PCA axis, confirming the significant impact of SMF treatments on plant metabolism.

The heatmap analysis (Figure 2) provided a more intuitive visualization of the effects of SMF treatments on the parameters and clarified group differentiation. Particularly in the 0.9 T and 1.1 T groups, parameters related to forage quality (ADF, NDF, crude protein, macronutrients) and antioxidant capacity (DPPH, total phenolic compounds) showed intense green (high) values, supporting the notion that these treatments enhance nutritional value and biological activity. Similarly, Mahajan and Pandey (2015) reported that SMF applications increase phenolic compound synthesis by activating the phenylpropanoid pathway. Meanwhile, increases in stress-related parameters such as SOD, proline, and APX were observed in the 0.5 T and 0.7 T treatments, indicating that these applications enhance the plant's defense capacity. This supports hypotheses suggesting that SMF can influence gene expression related to stress signaling (Florez et al., 2007).

Another noteworthy observation is the clustering of parameters within their respective categories. Pigments (Chl a, Chl b, carotenoids), antioxidant enzymes (SOD, CAT, APX), secondary metabolites (phenolics, tannins, flavonoids), and forage quality parameters (ADF, NDF, CP, Ca, K, Mg, P) were distinctly grouped. This separation indicates that SMF applications exert selective effects on different metabolic pathways. Previous studies have similarly reported positive effects of SMF on phytochemical content (Shine

et al., 2011), pigment synthesis (Zhang et al., 2017), enzyme activity (Radhakrishnan & Kumari, 2013), and mineral metabolism (Anand et al., 2012).

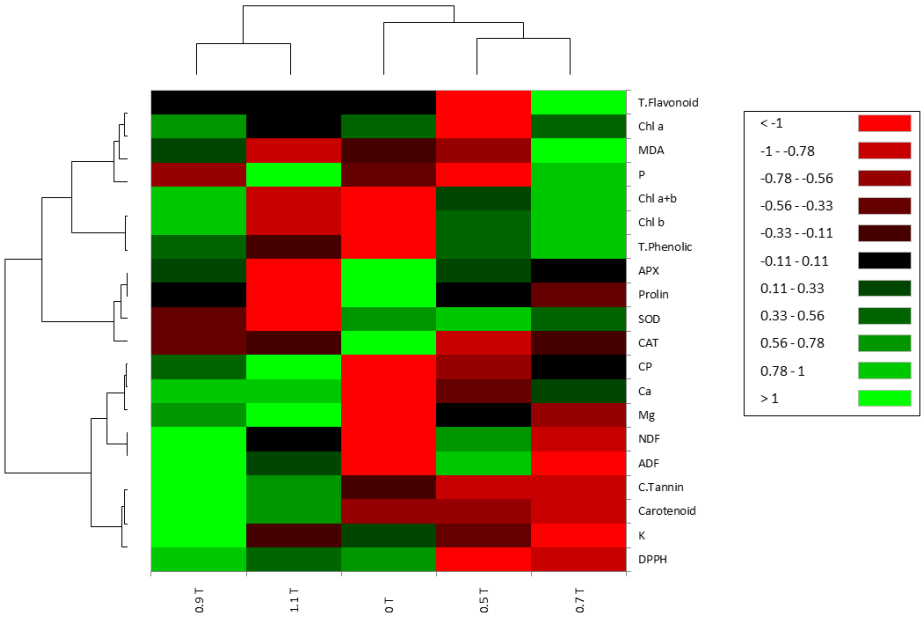

Figure 2. Heat map analysis of all examined parameters in different static magnetic field intensities

4. Conclusions

In this study, the effects of static magnetic field (SMF) treatments at different intensities (0, 0.5, 0.7, 0.9, and 1.1 Tesla) on the physiological, biochemical, and forage quality parameters of forage pea seeds were comprehensively evaluated. The findings revealed that SMF application significantly influenced both antioxidant defense systems and the production of secondary metabolites and macronutrient contents in a dose-dependent manner.

The 0.7 T and 0.9 T SMF treatments had particularly positive effects on parameters such as chlorophyll b, total phenolic compounds, flavonoids, crude protein, and antioxidant enzyme activities (SOD, APX), thereby improving forage quality. In the Principal Component Analysis (PCA) biplot, groups corresponding to these doses were positively associated with protein content and certain nutrients (Mg, Ca, K). Similarly, the heatmap analysis demonstrated that the 0.9 T treatment exhibited the most favorable profile in terms of phenolic compounds and nutrient contents. However, at the highest dose (1.1 T), decreases were observed in some parameters, which may indicate the onset of cellular-level stress responses. This finding suggests that the effects of SMF are dose-dependent and that intensities above a certain threshold may induce adverse effects.

In conclusion, SMF application had pronounced effects on the biochemical, antioxidant defense, and nutritional quality parameters of forage pea. These effects emerged in a dose-dependent manner, with the 0.9–1.1 T range considered optimal for improving forage value and metabolite richness. On the other hand, 0.5–0.7 T intensities were found to be more effective in enhancing plant stress physiology and tolerance responses. In this respect, the study demonstrates that SMF applications can be utilized in agricultural production systems in a purpose-driven and parameter-specific manner.

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