Selcuk Journal of Agriculture and Food Sciences

https://dergipark.org.tr/tr/pub/selcukjafsci

Research Article

(2024) 38(3), 533-541 DOI:10.15316/SJAFS.2024.047 e-ISSN: 2458-8377 Selcuk J Agr Food Sci

Magnetic Field Effect on Seed and Crude Oil Yields in Mustard (*Brassica Campestris*)

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HIGHLIGHTS

- Magnetic field seed treatment increases mustard yield in the field.
- The effect of the magnetic field treatment varies depending on the exposure time.
- The responses to the magnetic field application varied among the mustard varieties.
- Sustainable, cheap and easy treatment for increasing productivity has been proposed.

Abstract

Mustard (*Brassica campestris*) is an important spice and oil plant. Seed yield and oil quality of mustard vary depending on genetic, ecological, morphological, physiological, cultural, and environmental factors and their interactions. Increasing obtained seed or oil yield as the final product is of great economic importance. One of the innovative and environmentally friendly methods for increasing the efficiency and quality of plant production is magnetic field applications. Mustard varieties 'Tori' and 'Sarson' were used in the study to reveal their performances under the effect of magnetic field (MF) treatments. The 'Tori' and 'Sarson' seeds were exposed to 150 mT MF strength for different periods (0-control, 24, 48, and 72 hours). The highest seed and crude oil yields were obtained in 24-hour-MF treatment as 165.18 kg da^{-1} and 58.97 kg da^{-1}, with an increase of 43.39% and 38.72% according to the control treatment in the 'Tori' variety. In the 'Sarson' variety, seed and crude oil yields were recorded as 210.39 kg da^{-1} and 78.9 kg da^{-1}, respectively, with an increase of 54.03% and 44.4% according to control in 48-hour-MF treatment. This study reveals that MF treatment increased seed and crude oil yields in mustard, and the protocol could significantly contribute to the yields of other crop plants.

Keywords: Mustard; Magnetic field; Crude oil; Seed yield

1. Introduction

Against the rapidly increasing world population, food production is not growing at the same rate, and this shows that in each passing day, more and more people will be in danger of hunger and malnutrition. It is impossible to increase crop production areas to meet the growing needs of the world's food supply. The only way to increase plant production and yield is to increase the quantity of products obtained from the

Citation: Saykat MAR, Oguz CM, Oguz E, Yildiz M (2024). Magnetic Field Effect on Seed and Crude Oil Yields in Mustard (*Brassica campestris*). *Selcuk Journal of Agriculture and Food Sciences*, 38(3), 533-541. https://doi.org/10.15316/SJAFS.2024.047
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Received date: 22/08/2024

Accepted date: 25/11/2024

unit area. The fact that the interventions are environmentally friendly and renewable is among the important issues emphasized recently (Aboelazayem et al. 2018).

The economic independence of a country is directly proportional to energy source (Aslan and Eryilmaz 2020). From this point, the leading economic expenditure in production could be reduced with ecologically compatible renewable energy systems. Increasing the yield and quality obtained in agricultural output to the maximum level with environmentally friendly and sustainable methods is the aim for today and in the future. The application of seed priming methods by farmers in agricultural production can be successful as an alternative to chemical inputs (Oğuz et al. 2023). Inexpensive and environmentally friendly alternative sustainable methods will be preferred by the farmers when the increasing costs of chemical inputs are considered. Elimination/minimizing of chemical inputs in agriculture is highly important in achieving the "Sustainable Development Goals". Different seed preparation methods are known to increase plant performance effectively (do Espirito Santo Pereira et al. 2021). Seed preparation studies aim to maintain product yield sustainably and economically.

Brassicas are members of the *Brassicaceae* (*Cruciferae*) family (Rahman et al. 2018). *B. nigra* (2n = 16), *B.campestris* (2n = 20), *B. carinata* (2n = 34), *B. juncea* (2n = 36) and *B. napus* (2n = 38); are some of the important species (Hassan 2015; Kayaçetin et al. 2018). The *Brassica* family includes species with high oil and protein content. In addition; there are a wide variety of plant groups grown as vegetables, feed, and spices (Başbağ et al. 2010; Spragg 2016; Cartea et al. 2019). Mustard seeds have a high oil content of about 24-40%. Due to its high oil content, it is important in terms of vegetable oil and biodiesel production in the world (Başbağ et al. 2010; Al Snafi 2015; Aslan and Eryilmaz 2020). Seed yield and oil quality of mustard vary depending on genetic, ecological, morphological, physiological, cultural, and environmental factors and their interactions (Kayaçetin et al. 2018; Cartea et al. 2019). Increasing the seed or oil yield obtained as the final product is of great economic importance in mustard.

One of the innovative and environmentally friendly methods in increasing the efficiency and quality of plant production is magnetic field (MF) treatment. MF treatment enhances vegetative growth by influencing seeds' physiological and biochemical processes. It also improves product yield and quality (Pietruszewski and Martínez 2015; El-Gizawy et al. 2016; Beyaz et al. 2020; Aslan and Eryilmaz 2020). Many scientists have studied the positive and negative biological effects of MFs on living organisms. MF exposure to various plant species could result in different biological effects (Bilalis et al. 2013; El-Gizawy et al. 2016). MF treatment improved yield parameters and stress tolerance in many plant species such as sunflower (Matwijczuk et al. 2012), maize (Vashisth and Joshi 2017), potato (Bahadir et al. 2020), and sorghum (Beyaz et al. 2020) and barley (Okumuş et al. 2023). Most of the MF applications have been tested in laboratory trials. These studies mostly target the early stages of plant development, such as germination and seedling growth. Testing plant yield and yield parameters in field conditions is of great importance in determining the success of the treatment. Undoubtedly, the results will contribute to MF studies and new strategies (Pietruszewski and Martínez 2015).

In this study, an alternative method was investigated to increase mustard yield. It is the first study to determine the effects of MF seed treatment on yield parameters under field conditions in mustard. In this context, the aim was to determine the impact of different exposure times of 150 mT strength MF on seed and crude oil yields in the 'Tori' and 'Sarson' varieties.

2. Materials and Methods

This study was conducted in 2018 and 2019 in experimental fields of the Faculty of Agriculture, Ankara University. The study site was 860 meters above sea level. It was between 39° 57' north latitude and 32° 52' east longitude (Çatak 2019). The seeds of varieties 'Tori' and 'Sarson' were used in the study.

Analyzing soil samples belonging to the trial field was conducted at Ankara University, Faculty of Agriculture, Department of Soil. According to the analysis results, soil samples have pH 7.37, water saturation 61%, total salt 0.042%, quicklime (CaO) 5.66%, total N content 0.145%, phosphorus (P_2O_5) 5.52 kg da^{-1}, potassium (K_2O) 192 kg da^{-1} and organic compounds (1.05%).

2.1. Magnetic Field Generation & Treatment

The magnetic field system was established according to the protocol of Tanaka et al. (2010) with some modifications. Sintered magnets Nd-Fe-B banded N35 Atech, Beijing, China (https://www.atechmagnet.cn/) were used in the study. These magnets were squares of 50 mm x 50 mm x 10 mm in size with an average surface magnetic strength of 1.2 T (Tesla). Seeds were placed 2.83 cm above the surface of the magnets to provide 150 mT strength for different treatment periods. 150 mT MF strength was calculated according to the below formula (B = 0.15 T = 150 mT, FSM (Field Strength of Magnet) = 1.2 T, d (Distance)).

$$B = \frac{FSM}{d^2}$$

The 'Tori' and 'Sarson' seeds were exposed to 150 mT MF strength for different periods (0-control, 24, 48, and 72 hours).

2.2. Soil Preparation, Planting and Plant Development

The soil of the trial field was plowed 30 cm in depth in the fall before winter. In spring, it was plowed again 10-15 cm in depth to prepare soil for planting. Planting was performed in the third week of April with 30 cm row width spaces and 5 cm on-row. Three seeds were put in every hole to guarantee the germination. Two of the plants were eliminated two weeks after germination, and only one plant was left in every hole. During the development period of the seedlings, necessary irrigation and weed control were carried out. After flowering and fertilizing the plants, the tops of the plants were covered with perforated nets to protect the seeds from bird damage. The net gaps are large enough to prevent bird entry and provide sufficient light and airflow for the plants (Figure 1a-b).

2.3. Observations & Harvesting

The seed capsules obtained from the selected plants were collected in paper bags and kept at room temperature in the laboratory until blending and analysis processes. In the threshing process, the seeds in a capsule of each plant were collected in a different paper bag (Figure 1c-d).

Observations were performed in a total of 30 plants (10 plants per replication) for different MF periods. At the end of the study, seed yield per plant (g $plant^{-1}$), seed yield per decare (*kg* da^{-1}), crude oil content (%), and crude oil yield (kg da^{-1}) were determined as agronomic characters.

2.4. Determination of Seed Yield per Plant (g $plant^{-1}$)

Seed yield per plant was calculated by averaging the weights of seeds of 10 randomly selected plants for each replication of 150 mT MF strength for different treatment periods.

2.5. Determination of Seed Yield per Decare (kg da^{-1})

Seed yield per decare was calculated by multiplying seed yield per plant with the number of plants per decare for each replication of 150 mT MF strength for different treatment periods.

2.6. Determination of Crude Oil Content (%)

Crude oil content in percentage was calculated by averaging crude oil contents of seeds of 10 randomly selected plants for each replication of 150 mT MF strength for different treatment periods. The seeds were first grinded, and 2 g of grinded pieces were used to determine the crude oil content of the seeds. Crude oil content from seeds of mustard varieties was extracted in the soxhlet apparatus using petroleum ether as a solvent for 6 h according to the AOCS method (AOCS 1993).

2.7. Determination of Crude Oil Yield per Decare (kg da^{-1})

Crude oil yield per decare was calculated by multiplying crude oil content per plant with number of plants per decare for each replication of 150 mT MF strength for different treatment periods.

2.8. Statistical Analysis

The data were subjected to analysis of variance (ANOVA) using IBM SPSS Statistics 22 software. The field experiment was one factorial, completely randomized design, where a comparison was noted among different MF exposure times. The differences between the means in MF exposure time trials were determined using the Duncan test at 0.01. The difference between the varieties was not considered as a factor.

3. Results

The trials established with 150 mT MF treatment of mustard seeds for 24, 48, and 72 hours were completed. Images of the cultivation and post-harvest processes of mustard plants are given in Figure 1. The germination and seedling development of the seeds in the field were uniform. The positive changes in the production process of mustard under the influence of MF are summarized in Figure 2.

Figure 1. The flowering period of mustard plants (a), precautions taken to protect seeds from bird damage after flowering (b), samples collected after harvest (c), preparation mustard seeds for analysis (d).

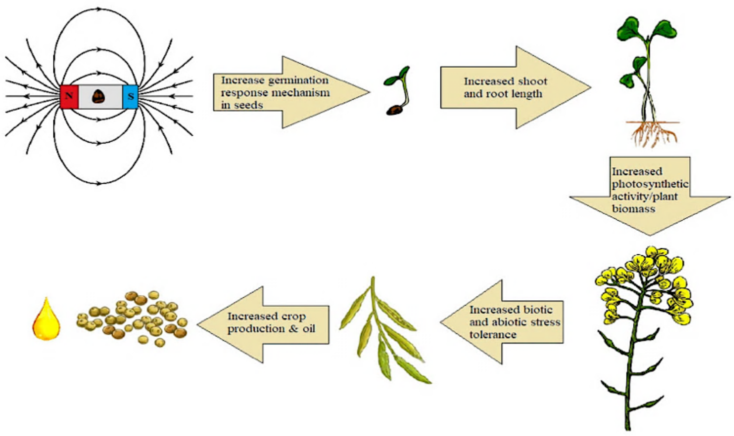

Figure 2. The effects of applying magnetic field intensity on different growth stages of mustard plants are illustrated. The mechanisms activated by seed stimulation increase the plant's tolerance to environmental stresses throughout the growth and development process. In addition to maximum utilization of nutrients and water in the soil, positive changes are observed in biochemical and physiological activities.

Seed yield was recorded as 115.20 kg da^{-1} in control while 165.18 kg da^{-1} in 24-hour-MF treatment as the highest in 'Tori'. In 'Sarson', seed yield increased to 210.39 kg da^{-1} in 48-hour-MF treatment from 136.59 kg da^{-1} in control. The increase in seed yield compared to control was recorded as 43.39% in 'Tori' and 54.03% in 'Sarson'. The mean increase percentage of the two varieties in seed yield was 48.71% (Table 1).

Table 1. The effect of 150 mT magnetic field strength at different treatment periods on seed yield, crude oil content and crude oil yield

Variety	Treatment Period (hour)	Seed Yield (kg da^{-1})	Increase in Seed Yield According to Control (%)	Crude Oil Content (%)	Crude Oil Yield (kg da^{-1})	Increase in Crude Oil Yield According to Control (%)
'Tori'	0-Control	$115.20^b \pm 2.85$	43.39	36.90	$42.51^b \pm 1.43$	38.72
	24	$165.18^a \pm 1.95$		35.70	$58.97^a \pm 1.81$	
	48	$106.80^b \pm 1.61$		34.80	$37.17^c \pm 0.92$	
	72	$98.79^b \pm 1.74$		35.80	$35.37^c \pm 1.66$	
'Sarson'	0-Control	$136.59^c \pm 2.00$	54.03	40.00	$54.64^c \pm 1.53$	44.40
	24	$136.20^c \pm 2.40$		34.80	$47.40^c \pm 2.00$	
	48	$210.39^a \pm 1.86$		37.50	$78.90^a \pm 1.50$	
	72	$171.18^b \pm 1.68$		36.60	$62.65^b \pm 1.51$	

*The difference between the averages shown with different letters for each variety is significant at 0.01 level.
*Each value is the mean of years 2018 and 2019

In 72-hour-MF treatment, seed yield was noted as 98.79 kg da^{-1} in 'Tori' and 171.18 kg da^{-1} in 'Sarson'. In 'Tori', seed yield started to decrease gradually from the highest value obtained in 48- and 72-hour-MF treatments (Figure 3a). The 'Sarson' cultivar showed a greater response than the 'Tori' cultivar to 150 mT MF treatment at different exposure times. Crude oil yield increased to 58.97 kg da^{-1} in 24-hour-MF treatment from 42.51 kg da^{-1} in control in 'Tori'. In 'Sarson', crude oil yield was 54.64 kg da^{-1} in control treatment while it was 78.90 kg da^{-1} in 72-hour-MF. Increase percentage in crude oil yield compared to control was obtained as 38.72% and 44.40% in varieties 'Tori' and 'Sarson', respectively. Overall mean of increase percentage of two varieties in crude oil yield was 41.56% (Table 1, Figure 3b). The highest crude oil contents were recorded as 36.90% and 40.00% in varieties 'Tori' and 'Sarson', respectively. Crude oil contents were determined as 35.70% in 24-hour-MF treatment in 'Tori' and as 37.50% in 48-hour-MF treatment in 'Sarson'. The differences in crude oil contents among different MF treatments in both varieties were found statistically insignificant (Table 1, Figure 3c).

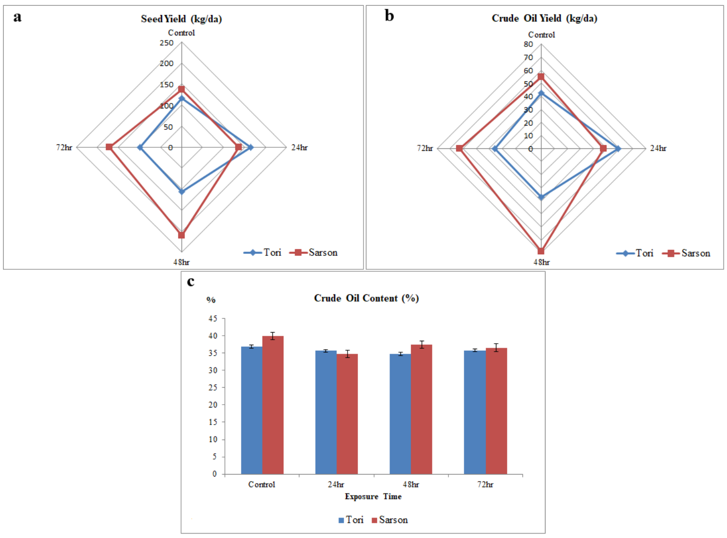

Figure 3. Effects of MF strength for different time periods on seed yield (kg da^{-1}) (a), Effects of MF strength for different time periods on crude oil yield (kg da^{-1}) (b), Effects of MF strength for different time periods on crude oil content rate (%) (c) in varieties 'Tori' and 'Sarson'.

Innovative and eco-friendly approaches such as bio-based technology, renewable energy, and sustainable agriculture are of great importance (Aslan and Eryilmaz 2020; Oğuz et al. 2023). MF treatment strategies are innovative and eco-friendly methods for improving seed germination, vegetative growth, abiotic stress tolerance and yield in most species (El-Gizawy et al. 2016; Beyaz et al. 2020; Okumuş et al. 2023). The MF treatment has the potential to have a positive effect at the cellular level. It could trigger biochemical, molecular, and physiological processes. The impact of the MF treatment could depend on the plant species, type of MF, strength, severity, and duration (Pietruszewski and Martínez 2015; Yildiz et al. 2017).

All living organisms are influenced by the Earth's magnetic field, also known as the geomagnetic field (GMF) (Maffei 2014; Pietruszewski and Martínez 2015). The intensity of the GMF ranges from 25 to 65 μT, and this variation is region-specific (Occhipinti et al. 2014). It has been reported that MF treatments lower than GMF values have negative effects on different physiological and molecular stages of plants (Belyavskaya 2004; Xu et al. 2013). Conversely, it has been stated that the MF treatment at higher rates than the GMF values gives positive results in plant species (Maffei 2014; Aycan et al. 2018; Beyaz et al. 2020). In the current study, under the effect of 150 mT of fixed MF, an increase in seed yield of 54.03% and oil yield of 44.40% was achieved in the 'Sarson' variety compared to the control. In the 'Tori' variety, seed yield increased 43.39% and oil yield increased 38.72%. The 150 mT MF used in the experiment is higher than the GMF as mentioned above. Our results support that high MF values cause an increase in yield parameters. Generally, the yellow seed varieties of *B. campestris* have higher oil content than the brown seed varieties (Hassan 2015). These differences in yield in the 'Tori' and 'Sarson' varieties are mainly due to variety differences. However, the efficiency of the fixed and long-term MF effect was increased compared to the control in both varieties.

MF effect affects a whole or specific structure in the living organism (Pietruszewski and Martínez 2015). The exposure of seeds to higher MF force than GMF increases seed germination and plant growth by increasing water assimilation and photosynthesis (Florez et al. 2007). Conversely, near-zero MF suppresses biomass accumulation in the generative period (Xu et al. 2013). This situation causes the plant to enter the flowering period late, grow late, and become vulnerable to the negative effects of the environment. Seeds exposed to a higher MF effect than GMF germinate faster and more uniformly. Rapid and uniform growth indicates that plants will gain superiority against environmental conditions during vegetative development. In our study, the 'Tori' and 'Sarson' seeds were exposed to a constant (150 mT) MF effect at different exposure times before planting. Although it varies according to the exposure time, a uniform development was observed in each trial plot during the germination, seedling, and flowering period (Figure 1a). According to the harvest results, the oil ratio (%) obtained from both varieties was measured less than the control. However, an increase in oil yield (kg da^{-1}) (38.72% in the 'Tori' variety, 44.40% in the 'Sarson' variety compared to the control) was determined. Seed and oil yield in oilseeds correspond to the total yield alone or together. The oil content (%) of the seeds can affect the obtained oil yield and the high seed yield, which can contribute to the oil yield obtained (Hassan 2015). As Pietruszewski and Martínez (2015) stated, MF effect studies have reported that it varies from μT (microtesla) to mT (miliTesla) and T (Tesla), and the results differ by up to 100 times compared to this. Despite these vast differences in the treated MF values, their effects seem similarly positive. However, in the results of our study; the yield at certain exposure times decreases were observed ('Sarson' variety, 24 and 72 hours). This result supports that the fixed MF effect does not always show a positive effect at different exposure times. In MF effect studies, the most important parameter, in addition to the magnetic field type and intensity, is the exposure time. Physiological, biochemical, and molecular analyses on this subject will contribute significantly to elucidating the MF effect mechanism.

Recently, a few studies have been conducted on the effect of magnetic fields on plant yield parameters. In the experiment conducted on the sunflower plants with the application of the magnetic field, it was determined that there was a significant increase in productivity. It has been observed that exposure of seeds to magnetic fields improves the integrity of the seed coat membrane and reduces cellular leakage and electrical conductivity (Vashisth and Joshi 2017). Similarly, magnetic field treatment for plant seeds has increasing yield parameters for plants growing from seeds, as shown in the current study result. Florez et al.

(2007) emphasized that corn seeds continuously exposed to 250 mT gave the best results in terms of germination and early growth of seedlings. Okumuş et al. (2023) reported increased salt stress tolerance in barley with 150 mT MF seed application. It was also stated that the examined parameters varied according to the exposure time. Vashisth and Joshi (2017) discussed the impact of changing magnetic field (MF) doses on specific seedling parameters in maize plants. The increase in MF strength didn't correspond with physiological development.

Additionally, there was no linear relationship between physiological development and exposure time. In this context, exploring the effects of continuous and consistent MF at different time intervals on various physiological and molecular plant responses is crucial. According to the results of the current study, the best seed yield in the Sarson variety was determined from 48 hours of MF exposure time (Figure 1a). Similarly, the best result regarding crude oil yield in the Sarson variety was determined from 48 hours of exposure time (Figure 1b). On the other hand, the best seed yield and crude oil yield in the Tori variety were determined from 24 hours of exposure time (Figure 1a-b). According to these results, the MF exposure time showed significant differences in yield parameters. Besides, the responses of varieties to MF treatment periods are different.

On the other hand, the effect of MF treatment and exposure times on crude oil content is insignificant (Figure 1c). In light of these results, it was determined that MF treatment and exposure times could have different effects depending on the plant's variety. In future studies, optimization of specific treatment doses and periods specific to species and varieties will increase the potential impact.

4. Conclusions

It was determined that the exposure of mustard seeds to constant MF effect for different exposure times stimulates yield parameters. In a discussion with other research results, it has been demonstrated that MF exposure time is equally essential to MF strength. Time factor is an important parameter to be considered in new optimization studies. Productivity and quality should be the main targets in meeting the needs of the increasing world population and determining the MF effect economically. The results were not carried out at the field condition and have no economic value remaining within the experimental dimension. This type of experiment is limited only to demonstrating the importance of the MF effect. Environmentally friendly and innovative agricultural approaches have become essential for ecological and sustainable life in the current order of the world. The aim of MF studies should be to reveal the potential yields of plant varieties at the highest. Studies on this issue require molecular, physiological, and economic perspectives.

Author Contributions: Conceptualization, M.A.R.S. and M.Y.; methodology, investigation, M.A.R.S.; writing—original draft preparation, M.C.O. and E.O..; writing—review and editing, M.A.R.S., M.C.O. E.O. and M.Y.; visualization, M.C.O. and E.O.; supervision, M.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study is not funded by any institution or organization.

Conflicts of Interest: The authors declare no conflict of interest.

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