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ARAŞTIRMA MAKALESİ / RESEARCH ARTICLE

EFFECT OF ELECTROMAGNETIC FIELD DERIVED FROM ELECTRIC FENCE SYSTEM ON SPERM ACTIVITIES OF HONEYBEES (*Apis mellifera* L.)

Elektrikli Çit Sistemi Tarafından Oluşturulan Elektromanyetik Alanın Bal Arılarının (*Apis mellifera* L.) Sperm Aktivitesine Etkisi

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ABSTRACT

This study investigated the effects of electromagnetic fields (EMFs) from electric fence systems on physiological and reproductive parameters of male honeybees (*Apis mellifera caucasica*). The study was conducted between May and August 2024 at the Bayburt University Beekeeping Application and Research Center, with five experimental groups. Hives were positioned at varying distances (1–2.5 m) from the fence. The findings showed that the average body weight (245.4 mg), sexual maturity rate (58.56%), and sperm concentration (0.87 ± 0.04 × 10 ^{6}/µL) of drones closest to the electric fence were significantly reduced (*p* < 0.05). The electric field effect was limited in groups at greater distances, with statistically insignificant differences in some parameters. No significant differences were found between groups in sperm volume. Results demonstrate that electric fields from fence systems suppress developmental processes and reproductive physiology of drones in a distance-dependent manner. Lower body weight, decreased sperm concentration, and proportion of mature males in colonies near the fence show electromagnetic stress is a significant risk for bee health. Future studies should examine the effects of electromagnetic fields at different frequencies and strengths on larval development, sperm morphology, oxidative stress markers, and gene expression profiles.

Key words: Honey bee, Electric fence, Electromagnetic field, Sperm quality, Drone

ÖZ

Bu çalışma, elektrikli çit sistemlerinden kaynaklanan elektromanyetik alanların (EMA) erkek bal arılarının (*Apis mellifera caucasica*) fizyolojik ve üreme parametreleri üzerindeki etkilerini araştırmak amacıyla yürütülmüştür. Çalışma, Mayıs-Ağustos 2024 tarihleri arasında Bayburt Üniversitesi Arıcılık Uygulama ve Araştırma Merkezi'nin yazlık arılığında gerçekleştirilmiş ve beş farklı deney grubu oluşturulmuştur. Kovanlar, çitten farklı mesafelere (1-2.5 m) yerleştirilmiştir.Bulgular, elektrikli çite en yakın kolonilerdeki erkek arıların ortalama vücut ağırlığının (245,4 mg), cinsel olgunluk oranının (%58.56) ve sperm konsantrasyonunun (0.87 ± 0.04 × 10^{6}/µL) önemli ölçüde azaldığını göstermiştir (*p* < 0.05). Buna karşılık, elektrik alan etkisi daha uzak mesafelerdeki gruplarda sınırlı kalmış ve bazı parametrelerde istatistiksel olarak anlamsız farklılıklar gözlenmiştir. Sperm hacmi açısından gruplar arasında anlamlı bir fark bulunamamıştır. Sonuçlar, elektrikli çit sistemleri tarafından üretilen elektrik alanının, erkek arıların gelişim süreçlerini ve üreme fizyolojisini mesafeye bağlı olarak baskıladığını göstermektedir. Çite yakın kolonilerde gözlenen düşük vücut ağırlığı, azalmış sperm konsantrasyonu ve olgun erkek arı oranı, elektromanyetik stresin arı sağlığı için önemli bir risk faktörü olduğunu göstermektedir. Farklı frekans ve güçlerdeki elektromanyetik alanların larva gelişimi, sperm

morfolojisi, oksidatif stres belirteçleri ve gen ifadesi profilleri üzerindeki etkilerinin kapsamlı bir şekilde incelenmesi için gelecekteki çalışmalar önerilmektedir.

Anahtar kelimeler: Bal arısı, Elektrikli çit, Elektromanyetik alan, Sperm kalitesi, Erkek arı

GENİŞLETİLMİŞ ÖZET

Amaç: Elektromanyetik alanların (EMA) canlı organizmalar üzerindeki etkileri uzun süredir tartışılmaktadır. Elektrikli çit sistemleri de yüksek voltajlı kısa süreli darbeler (impuls) üreterek çalışan ve özellikle tarımsal alanlarda yaygın kullanılan yapılardır. Bu sistemlerde esas etki elektrik alan şiddeti üzerinden gerçekleşmekte, manyetik alan ise devreden geçen akımın düşük olması nedeniyle ihmal edilebilir düzeyde kalmaktadır (Gajšek, Ravazzani et al. 2016, Erdoğan Y 2019). Son yıllarda, elektromanyetik alanların bal arılarının davranışsal ve fizyolojik süreçleri üzerinde olumsuz etkiler oluşturabileceğine yönelik çalışmalar artmıştır. Ancak yüksek çıkış gücüne sahip elektrikli çit sistemlerinin arılar üzerindeki etkilerine dair veriler sınırlıdır. Bu çalışma, elektrikli çit sistemine farklı mesafelerde bulunan kolonilerde erkek bal arılarının (***Apis mellifera caucasica*** melezi) fizyolojik ve üreme parametrelerinde meydana gelen değişimleri ortaya koymayı amaçlamaktadır.

Gereç ve Yöntem: Araştırma, 2024 yılı Mayıs–Ağustos ayları arasında Bayburt Üniversitesi Arıcılık Uygulama ve Araştırma Merkezi'nde yürütülmüştür. Beş grup halinde düzenlenen denemede, her biri aynı güce sahip koloniler elektrikli çite farklı mesafelerde (1, 1.5, 2, 2,5 m) konumlandırılmıştır. Elektrikli çit sistemi 30.000 V gerilim üreten bir cihazla kurulmuş ve kovan içi elektrik alan değerleri 0,20–555,3 mV/m arasında ölçülmüştür. Deneme süresince her gruptan belirli aralıklarla erkek arılar toplanmış, vücut ağırlıkları kaydedilmiş, cinsel olgunluk oranları hesaplanmış ve semen örnekleri değerlendirilerek sperm hacmi ile konsantrasyonu belirlenmiştir.

Bulgular: Sonuçlar, özellikle çite 1 m mesafedeki (Grup II) kolonilerde belirgin farklılıklar ortaya koymuştur. Bu gruptaki erkek arıların ortalama vücut ağırlığı 245,4 mg'a düşmüş, cinsel olgunluk oranı %58,56'ya gerilemiş ve sperm konsantrasyonu 0,87 ± 0,04 × 10^6/μL'ye kadar azalmıştır. Buna karşılık daha uzak mesafelerdeki (Grup IV ve V) kolonilerde elektrik alan değerleri daha düşük (193–293 mV/m) bulunmuş ve üreme parametrelerindeki bozulmalar sınırlı düzeyde kalmıştır. Sperm hacmi açısından ise gruplar arasında istatistiksel olarak anlamlı bir farklılık yoktur ($p < 0.05$).

Sonuç: Elde edilen bulgular, elektromanyetik alan şiddetinin artışıyla erkek arıların gelişimsel süreçlerinin ve üreme fizyolojisinin baskılandığını göstermektedir. Bu sonuç, elektromanyetik stresin oksidatif metabolizmayı etkilediğini ve gen ekspresyonunu değiştirdiğini bildiren önceki çalışmalarla uyumludur (Panagopoulos, Johansson et al. 2015, Migdal et al. 2023). Buna karşılık bazı araştırmalarda düşük seviyeli elektromanyetik alanların arılar üzerinde istatistiksel olarak önemsiz etkiler gösterdiği bildirilmiştir (Vilić Gajger et al. 2017). Bu durum, çalışmamızda daha uzak mesafelerde gözlenen sınırlı etkiyi destekler niteliktedir. Dolayısıyla, elektrikli çit sistemlerinin arılar üzerindeki etkisinin maruziyetin şiddeti, süresi ve gelişim evresine bağlı olarak değişkenlik gösterdiği anlaşılmaktadır.

Bu çalışma, yüksek çıkış gücüne sahip elektrikli çit sistemlerinin erkek bal arılarında mesafeye bağlı ve doza bağımlı olumsuz etkiler oluşturabileceğini ortaya koymuştur. Özellikle çite yakın kolonilerde gözlenen düşük vücut ağırlığı, azalmış sperm konsantrasyonu ve cinsel olgunluk oranı, elektromanyetik stresin arı sağlığı açısından dikkate alınması gereken bir risk faktörü olduğunu göstermektedir. Gelecekte yapılacak çalışmalarda, farklı frekans ve güç seviyelerindeki elektromanyetik alanların larva gelişimi, sperm morfolojisi, oksidatif stres belirteçleri ve gen ekspresyon profilleri üzerindeki etkilerinin incelenmesi, mekanizmaların daha net anlaşılmasına katkı sağlayacaktır.

INTRODUCTION

Areas where bee colonies are kept together are called apiaries. Bee colonies are generally established in high-altitude areas, where flowers persist for extended periods; however, these areas also constitute natural habitats for bears. Various methods have been developed to protect colonies from these pests, and one of the most effective and widely used methods is electric fencing. Electric fences operate by sending high-voltage electrical pulses through conductive wires. Each pulse creates an electromagnetic field (EMF) around the wires. It is believed that this field may have biological effects on honeybees.

An electromagnetic field is a physical phenomenon that consists of a combination of electric and magnetic fields. In modern life, it is emitted from many sources, including electrical appliances, wireless communication systems, GSM base stations, and high-voltage power lines, and has become an environmental factor to which living things are constantly exposed (Abd El Rahman, Abd El Hady et al. 2014, Khaki, Zarrintan et al. 2008).

It has been reported that exposure to electromagnetic fields can affect various physiological and biochemical processes in both humans and animals. Studies conducted on mammals have revealed that long-term electromagnetic field exposure can cause tissue damage in various organs, particularly negatively impacting the reproductive system (Agarwal et al. 2008, Aydin et al. 2007, Forgács et al. 2004)

Some studies have reported decreased sperm motility and viability (Mailankot et al., 2009), but no significant change in sperm count (Gutschi et al. 2011) has been observed. These findings suggest that the effects of electromagnetic fields on reproductive biology are complex and vary across species.

There are also studies suggesting that electromagnetic environments can influence the behavior and physiology of honeybees. Some studies have reported that electromagnetic exposure can affect bees' navigational abilities and behavior (Kumar et al. 2009, Sharma and Kumar 2010). The World Health Organization also emphasizes the need to prioritize research on the potential effects of electromagnetic fields on animal health (Cucurachi et al. 2013).

In this context, examining the potential effects of electromagnetic fields generated by electric fences used to protect bee colonies from bear attacks on the reproductive parameters of male honeybees is an important research topic.

This study aims to evaluate the effects of electromagnetic fields generated by electric fence systems on the semen parameters of male honeybees.

MATERIALS AND METHODS

Study Area

This study was conducted in 2024 at the summer apiary of the Beekeeping Application and Research Center of Bayburt University Demirözü Vocational School. The experiment was conducted between May and August.

Experimental Design

The study included healthy bee colonies of similar strength, each with 8 frames and 5 frames of brood. Twenty-five colonies with one-year-old Caucasian hybrid queens were used in the study. Colonies were placed in standard Langstroth-type wooden hives and randomly divided into five experimental groups.

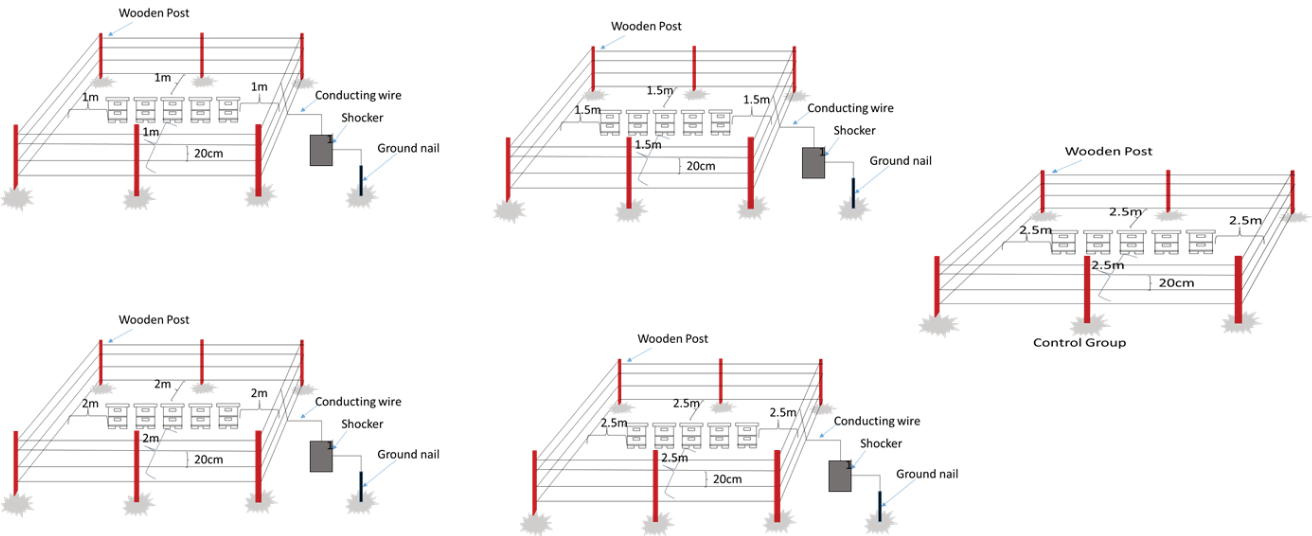
To ensure age synchronization in drones, frames with printed drone eyes, previously embossed on strong colonies, were placed inside a plastic cage with a queen bee grid. The queen was placed inside this cage and placed in the brood nest. After 24 hours, the frame and queen were removed from the cage (Hamednia 2012).

The colonies were divided into five groups based on their distance from the electric fence wires (Table 1, Figure 1). All groups except the control group were surrounded by an electric fence within the experimental area.

The electric fence system was established using a device generating 30.000 V. The fence was constructed from stacks of five steel wires, with a 20 cm distance between each wire. A minimum distance of 5 m was maintained between experimental groups to prevent electromagnetic field interference.

Table 1. Distances of the experimental groups to the electric fence.

Experimental groups	Distance to electric fence wires (m)
I.	Control
II.	1
III.	1.5
IV.	2
V.	2.5



Şekil 1. Installation diagrams of the electric fence system employed in the experiment.

Measurement of electromagnetic field (EMF) and electric field (EF) intensity

Electromagnetic field values originating from the fence system were measured from the distance of the hives using TES 593 and TES 1393 electromagnetic frequency meters. Average values were obtained from repeated measurements taken on different mornings and evenings. Because the electric fence system delivers pulses of electricity to the wires at regular intervals, the device monitors constantly changing values. The lowest and highest measured electric field intensity values were recorded and averaged.

Because the current flowing through the fence wires was very low, the magnetic field was quite weak. A small, brief magnetic field was generated only during the impact (during the high-voltage discharge), but this effect was negligible compared to the electric field (Table 2).

Drone Weight

Semen parameters of drones were determined between 26 and 30 days of age, the period of sexual maturity. Live weights of individuals were recorded using a laboratory balance (RADWAG AS 220.R2) with a measurement accuracy of 0.1 mg. Weight measurements were performed on 100 individuals from each experimental group (Rinderer et al. 1985, Shoukry et al. 2013).

Mature Drone Percentage

100 drones randomly selected from the experimental colonies were assessed for maturity using the manual endophallus eversion method. Individuals with semen release from the genital tip during eversion were classified as "mature." In cases where semen release was confirmed, samples were collected and recorded using a micropipette. The mature drone percentage was calculated using the following formula (Harbo 1985, Yániz et al. 2020, Metz and Tarpy 2022).

$$Mature\ drone\ ratio = \frac{Number\ of\ drones\ sampled\ and\ confirmed\ as\ mature}{Total\ number\ of\ drones\ sampled} X100$$

Semen Collection from Drones and Determination of Semen Volume

From the beginning of the experiment, 100 drones were randomly selected from each group at 3:00 PM each day. Semen was obtained from the selected individuals using the endophallus eversion method (Harbo 1985)

and collected with a micropipette calibrated to 1 μL. The semen volume for each individual was determined by measuring the length of the liquid in the pipette using a caliper.

Sperm Viability

The collected samples were mixed with a modified Kiev diluent solution (Kaftanoglu and Peng). Sperm viability was determined using the LIVE/DEAD Sperm Viability Kit (Invitrogen, USA) (Collins and Donoghue 1999). Live cells fluoresced green with SYBR-14, while dead cells fluoresced red with propidium iodide. Stained samples were examined under a fluorescence microscope (Olympus IX51, Olympus America Inc., USA) and evaluated using appropriate filters.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics 22.0 (IBM Corp., Armonk, NY, USA). Data are presented as mean ± standard error (SE). Differences between groups were assessed using one-way analysis of variance (ANOVA), and the Duncan multiple comparison test (post hoc) was applied for significant differences. A P value of <0.05 was considered statistically significant in all analyses.

RESULTS

EF and EMF values measured from test hives

After activating the electric fences, EF and EMF intensity values were measured inside the hives of the experimental groups (Table 2). Consequently, no significant difference was found between the electromagnetic radiation (μT) levels of the different treatments. However, significant differences occurred in the electric field intensity (mV/m) values. While both the minimum and maximum electric field values were found to be quite low in the control group (Group I), the highest electric field intensity (555.3 ± 52.46 mV/m) was recorded in Group II. The electric field values of Groups III, IV, and V, although statistically different, remained lower than in Group II. These findings indicate that the electric field intensity varied significantly between treatments, while the magnetic field levels remained constant.

Table 2. Electric field and electromagnetic radiation values measured inside the beehives in the experimental groups. Different lowercase letters in the same column indicate statistically significant differences between treatments ($p < 0.05$, one-way ANOVA, Tukey's HSD test). The actual p-values are presented in the last row of the table.

Applications	Electromagnetic radiations (μT) $\bar{x} \pm S\bar{x}$	Electric field (mV/m) $\bar{x} \pm S\bar{x}$ (minimum values)	Electric field (mV/m) $\bar{x} \pm S\bar{x}$ (Maximum values)
1	0.089 ± 0.001^a	0.20 ± 0.10^a	2.14 ± 0.34^a
2	0.095 ± 0.002^a	319.6 ± 28.08^d	555.3 ± 52.46^d
3	0.090 ± 0.001^a	227.8 ± 50.49^c	425.5 ± 71.22^c
4	0.095 ± 0.003^a	211 ± 37.48^b	342.6 ± 51.93^c
5	0.090 ± 0.002^a	193 ± 40.97^b	293.3 ± 33.68^b
***P*-value**	0.243 ns	<0.001	<0.001

*Values are expressed as mean ± standard error ($\bar{x} \pm S\bar{x}$). Statistical differences were analyzed using one-way ANOVA among rows (between treatments) within each column. different letters indicate significant differences ($p < 0.05$). "ns" indicates non-significant differences.

Drone Weight

The body weight of drones is a fundamental biological indicator that can be detailed in terms of their overall vitality, metabolic capacity, and division performance. Therefore, changes in body development can be considered a direct consequence of the increased stress drones face during development. In our study, the body weights of drones obtained from colonies exposed to high-powered electric fence systems and those exposed to EMF were compared, although a decreasing trend was observed in the experimental colonies located closer to the fence, **no statistically significant differences were found among the groups** ($p > 0.05$) (Figure 2).

The findings indicate a systematic weight loss in the experimental groups compared to the control group. The average weight was 246.79 mg in the Control Group (Group I), while the lowest value was 245.4 mg in the experimental colonies closest to the fences (1 m) (Group II) (Figure 2). Drone weight increased as the hives moved away from the fence. Despite this pattern, the Duncan multiple comparison test confirmed that the differences were not statistically significant, indicating that the proximity to the fence did not have a distinct effect on drone body weight.

However, the Duncan multiple comparison test showed that the experimental groups were not statistically different from each other, and that the degree of proximity to the fence did not have a different effect on drone weight.

Overall, the findings suggest that exposure to high-output electric fence systems may have a mild impact on the physiological development of drones. Nevertheless, these differences were not statistically significant. The slight reduction in body weight observed in the experimental colonies seems to reflect a natural biological response to environmental stress rather than a measurable developmental impairment.

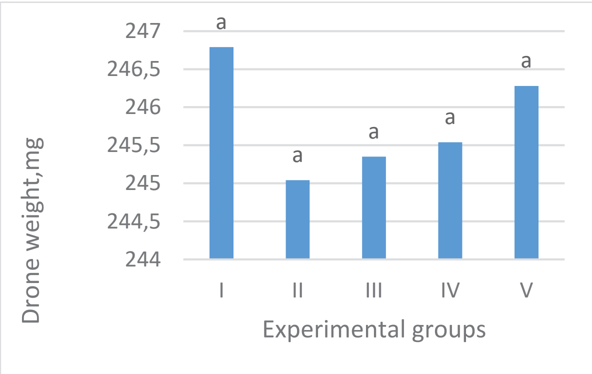


Figure 2. Average body weights of drones from colonies positioned at different distances from the electric fence system. Experimental groups: I = Control (no exposure), II = 1 m, III = 1.5 m, IV = 2 m, V = 3 m from the fence. Although colonies located closer to the fence tended to produce slightly lighter drones, these differences were not statistically significant ($p > 0.05$; Duncan's multiple comparison test). Values are presented in milligrams (mg).

Mature Drone Rate

To collect fresh sperm samples and assess their quality parameters, 100 drones from each group were placed in specially prepared cages to determine their sexual maturity. The ratio of sexually mature individuals to the total population was calculated, and comparisons were made between groups (Figure 3).

While the highest sexual maturity rate was observed in the control ranges, a significant decrease was found in this rate in all other experimental groups ($p < 0.05$). The decrease observed in Group II was particularly notable (Figure 3). The highest proportion of drones reaching sexual maturity was found in Group I (78.51%), while the lowest was found in Group II (58.56%) (Figure 3). Duncan's post-hoc test results showed statistically significant differences between the experimental groups ($p < 0.05$). In experimental groups IV and V, drones were placed in the same group, while the others were placed in different groups. The findings suggest that prolonged use of electric fences may negatively affect the rate of drones reaching sexual maturity.

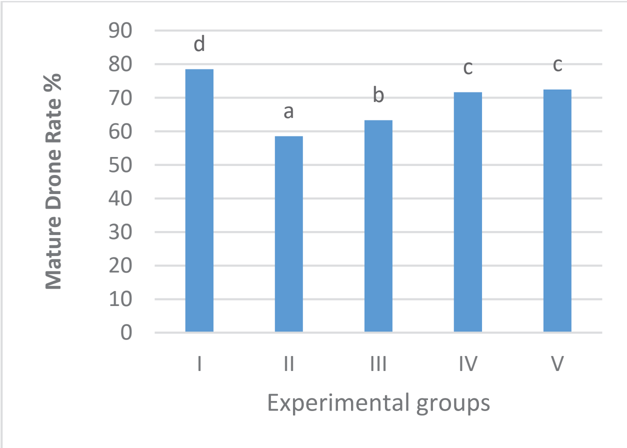


Figure 3. Drone sexual maturity rates in colonies positioned at different distances from the electric fence system. Experimental groups: I = Control (no exposure), II = 1 m, III = 1.5 m, IV = 2 m, V = 3 m from the fence. Colonies closer to the fence exhibited lower sexual maturity rates compared to the control, and these differences were statistically significant ($p < 0.05$; one-way ANOVA followed by Tukey's HSD test).

Semen Volume

Comparison of the mean volume values of drone sperm obtained from the experimental groups revealed no statistically significant differences between the groups ($p < 0.05$; Table 3). Multiple comparison analyses revealed that all treatment groups exhibited similar mean values and were in the same statistical group. The highest mean sperm volume value was 0.92 ± 0.11 μL in Treatment Group I, while the lowest was 0.88 ± 0.09 μL in Treatment Group II. These results suggest that the magnetic and electric fields generated by the electric fence system had limited effects on drone sperm volume, but these effects were not statistically significant.

Sperm Viability

Environmental stress factors can negatively affect sperm fertilization capacity. Sperm viability and sperm concentration are among the most critical parameters in assessing drone sperm quality, and these parameters are considered reliable indicators of reproductive success (Table 3). In this study, viability rates were compared in sperm samples obtained from drones exposed to the magnetic field generated by an electric fence system installed at different distances around the apiary, and statistically significant differences were identified between the treatments (p < 0.05). While no significant difference was found between Groups II and III, both groups had lower sperm viability rates compared to the control group (96.57 ± 0.52%), and these groups were placed in statistically different classes. The findings indicate that electric fence systems can negatively affect sperm cell viability. Significant differences in sperm quality were observed in colonies located 1 and 1.5 meters from the electric fence, suggesting that closer proximity to the fence may adversely affect drone reproductive capacity.

Sperm Concentration

In the concentration analysis of sperm samples obtained from drones, the highest value was recorded in the control group (Group I; 1.83 ± 0.11 × 10^6/μL). This was followed by Group V (1.51 ± 0.39 × 10^6/μL), Group IV (1.33 ± 0.13 × 10^6/μL), Group III (1.31 ± 0.27 × 10^6/μL), and the lowest value in Group II (0.87 ± 0.04 × 10^6/μL). The differences between the groups were determined to be statistically significant (p < 0.05). According to the results of the Duncan multiple comparison test, Groups III and IV were in the same class, while Groups IV and V were in different classes. In contrast, Groups I and II were found to be in different classes (Table 3).

The findings indicate that decreasing the distance from high-output electric fence systems suppresses spermatogenesis in drones, resulting in a significant decrease in sperm concentration. The low values obtained from colonies closest to the fence, in particular, indicate that electromagnetic field exposure can have serious and negative effects on reproductive physiology.

While significant differences were observed in sperm concentration between the experimental groups, no similar changes were observed in semen volume and viability. This may be due to the regulation of these traits by different physiological mechanisms. Sperm concentration is more sensitive to nutritional status, temperature changes, or electromagnetic effects during development. In contrast, sperm viability and volume are more stable indicators of semen quality. Therefore, the decrease in sperm concentration alone suggests that the electric field affects spermatogenesis rather than overall seminal structure.

The sperm concentration values obtained in this study are slightly lower than the previously reported average values, including those of the control group (Collins 2000, Gençer and Kahya 2020, Yániz, Silvestre et al. 2020). This difference is thought to be related to factors such as colony strength, drone age, seasonal conditions, and the physiological state of the drones at the time of sampling. A similar low cell density has been reported in cases where environmental or management conditions are unfavorable (Yániz, Silvestre et al.,. Therefore, it can be argued that the relatively low values in our study are due to environmental, not methodological, differences; however, the differences between groups reflect the potential effects of electromagnetic exposure.

Table 3. Sperm parameters [viability (%), density (×10^6/μL), volume (μL)] in *Apis mellifera caucasica* hybrid drones exposed to electric fence at different distances. Different letters in the same row indicate statistical differences between groups (p < 0.05; Duncan test).

Parameters	Experimental groups				
	I.	II.	III.	IV.	V.
Semen volume (μL)	0.92 ± 0.11^a	0.88 ± 0.09^a	0.89 ± 0.19^a	0.90 ± 0.09^a	0.91 ± 0.09^a
Sperm viability (%)	96.57 ± 0.52^d	90.81 ± 0.72^a	92.43 ± 0.18^{ab}	93.59 ± 0.39^{bc}	94.39 ± 0.34^c
Sperm concentration X10^6/ μl	1.83 ± 0.09^c	0.87 ± 0.04^a	1.31 ± 0.27^{ab}	1,33 ± 0.13^{ab}	1.51 ± 0.39^{bc}

*Data are presented as mean ± standard error ($\bar{x} \pm S\bar{x}$). Statistical comparisons were made within each parameter using one-way ANOVA followed by Duncan's multiple range test. Different lowercase letters in the same row denote statistically significant differences among groups (p < 0.05).

DISCUSSION

The findings from this study indicate that there are significant differences in the physiological and reproductive parameters of drones in colonies located close to a high-output electric fence system. Electric fence systems essentially operate as structures that generate short-duration pulses from a high-voltage source, and the primary effect in these systems is the strength of the electric field. Because the current flowing through the circuit is very low, the magnetic field strength is generally negligible. Indeed, studies measuring electric and magnetic field values within the hive confirm this approach (Erdoğan 2019).

Similarly, reviews of low-frequency electric and magnetic field exposure indicate that magnetic effects are limited in most cases (Gajšek et al. 2016). It is particularly noteworthy that in colonies located 1 m from the fence wires (Group II), the electric field value was measured in the range of 319.6–555.3 mV/m. This parallel decrease in the average body weight of drones to 245.4 mg, the sexual maturity rate to 58.56%, and the sperm concentration decreased to $0.87 \pm 0.04 \times 10^6$/µL. This suggests that both the developmental process and the reproductive physiology of drones are suppressed as the electric field intensity increases. Similar findings supporting the effects of electromagnetic fields on bee physiology are also available in the literature. For example, 900 MHz RF-EMF exposure has been reported to increase oxidative stress markers in bee hemolymph , 2023), alter the activities of AST, ALT, and ALP enzymes, and affect stress-related gene expression. Another study indicated that electromagnetic radiation (EMF) can harm the health of honeybees in the long term, and that the negative impact increases as the bee approaches the EMF source (Taye et al. 2018).

Studies have also shown that cell phone radiation can reduce the queen's egg-laying capacity (Sainudeen Sahib 2011, Sharma and Kumar 2010). Research findings also indicate that the lipid content in the hemolymph of honeybees increases, while certain enzyme levels decrease, in response to EMF exposure (Kumar et al. 2016). Similarly, studies have shown that reproductive cell viability decreases and developmental disorders increase in insects exposed to electromagnetic waves (Panagopoulos et al. 2015). These studies suggest that the low body weight and deterioration in sperm parameters observed in Group II may be related to the negative effects of electric field-induced stress on cellular energy metabolism and tissue development from the larval stage onward.

However, some studies have reported limited or statistically insignificant effects of low-level electromagnetic fields on bees (Vilić et al. 2017). This finding is consistent with the mild effects observed at greater distances (211–293 mV/m) in Groups IV and V in our study. Therefore, the effects of electric fence systems on bees appear to vary depending on the intensity, duration, and stage of development at the time of exposure.

While electromagnetic exposure is the primary effect of electric fence systems, pulsed operating mechanisms can also produce rhythmic clicking sounds and low-amplitude mechanical vibrations. These secondary stimuli could theoretically serve as an additional stressor. Based on current knowledge, peer-reviewed studies directly assessing the acoustic or vibrational effects of electric fences on honeybees are extremely limited. However, honeybees are known to be highly sensitive to both acoustic and substrate-borne vibrations Abdollahi et al. 2022, (Kirchner 1993), and anthropogenic noise has been shown to negatively impact pollinator behavior and plant reproductive success in some ecosystems (Goulson and Rotheray 2012). Therefore, it should not be ruled out that these secondary stimuli may also play a role in some of the effects observed in colonies closest to the fence. Separating the electromagnetic effect from the sound and vibration components in future research will contribute to a clearer understanding of potential interaction mechanisms.

Although the study design initially planned to analyze sperm motility, technical issues encountered during the fluorescent staining procedure prevented the collection of reliable motility data. Therefore, motility was not included among the parameters evaluated. Future studies will incorporate robust motility assessment methods to provide a more comprehensive assessment of drone reproductive performance under electromagnetic exposure.

Conclusion

Overall, this study demonstrates that high-output electric fence systems can have distance- and dose-dependent negative effects on the physiological development and reproductive capacity of drones. The weight loss, low sperm concentration, and decreased proportion of mature males observed in colonies close to the fence demonstrate that electric field-induced stress is a significant risk factor for bee health. Future studies examining the effects of electromagnetic fields at different frequencies and power levels on larval development, sperm morphology, oxidative stress markers, and gene expression profiles will contribute to a clearer understanding of these mechanisms.

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Data Availability: The data used are based on the availability of the article and can be shared by the author upon reasonable request.

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