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An experimental study on the effect of non-ionizing electromagnetic fields on honey bees

Nilüfer As[a], Yasin Karan[b], Serdar Dizman[a], Betül Ceylan Sayi[a], Ahmet Kuvanci[c], Şeref Cinbirtoğlu[c], Seyit Hasan Öztürk[c], and Mustafa Ergin Şahin[b]

[a]Department of Physics, Faculty of Arts and Sciences, Recep Tayyip Erdoğan University, Rize, Türkiye; [b]Department of Electrical and Electronics Engineering, Recep Tayyip Erdoğan University, Rize, Türkiye; [c]Ministry of Agriculture and Forestry Apiculture Research Institute, Ordu, Türkiye

ABSTRACT

Due to the increase in data rate in mobile communication and the widespread use of mobile internet, electromagnetic communication systems are increasing daily. This situation causes increases in the use of more mobile communication devices and environmental non-ionizing Electromagnetic Field (EMF) levels. The rise of bee deaths and colony losses in beekeeping parallel to the increase of the EMF sources cause the concept of "electromagnetic pollution" to be considered among the reasons. Therefore, studying the effects of non-ionizing Electromagnetic Radiation (EMR) on the health of living things is one of the most significant issues today. The bees determine their direction with the Earth's magnetic field. Electromagnetic signals emitted by GSM base stations, etc. may affect the direction-finding capabilities of honey bees and constitute a stress factor. In this study, the aim was to determine the effect of EMF on honey bees and honey yield. Honey bee colonies were used, obtained from the same farm in the Trabzon region, and equalized in all respects. Moreover, these colonies were divided into five groups randomly as experiments and control groups. The experiment hives were exposed to the EMF in the frequency band of the Wi-Fi signals (2.4 GHz) and the high-voltage line (50 hz). The control hives are located far away from the EMR sources. The study was repeated in the second year to confirm the results. During the investigation, some physiological and behavioural effects of bees, such as aggressiveness, brood area, etc. were determined based on EMR exposure.

PLAIN LANGUAGE SUMMARY

- Studying the effects of non-ionizing Electromagnetic Radiation (EMR) on the health of living things is one of the most significant issues today.
- In this study, the aim was to determine the effect of EMF on honey bees and honey yield.
- Honey bee colonies were used, obtained from the same farm in the Trabzon region, and equalized in all respects.
- During the investigation, some physiological and behavioural effects of bees, such as aggressiveness, brood area, etc. were determined based on EMR exposure.

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KEYWORDS
Honey bee; electromagnetic field; Wi-fi; high voltage power line; honey

Introduction

With the development of technology and industrialization, the demand for energy transmission lines, transformer centers, and various antenna systems, such as radio and television transmitters, is increasing. In addition, advancements in communication and information technologies, which involve using computers, software, and networks to process and manage data, generate electromagnetic fields. For example; wireless local area networks (WLAN), bluetooth, multimedia message service, short message service and video call applications that all used a few of them (Karan and As 2016). The use of mobile communications systems has reached peak levels. Electromagnetic fields (EMF) generated by these systems are increasingly integrated into human lives with greater diversity and power every day (Karan et al. 2017). For this reason, EMF exposure in the radio frequency (RF) region (10 kHz-300 GHz) is increasing day by day (As et al. 2014).

Electromagnetic field intensity in the environment is also considered within the scope of environmental pollution. In recent years, measurement studies that determine the density of these areas in the environment have gained importance (Dilek et al. 2021; Memişoğlu 2019; Sayi 2020; Şahin et al. 2013). Since, unlike other environmental pollutions, it is not visible to the naked eye, and its effects do not appear immediately. However, it should not be ignored that it may affect living things.

CONTACT Mustafa Ergin Şahin mustafa.sahin@erdogan.edu.tr Department of Electrical and Electronics Engineering, Recep Tayyip Erdoğan University, Rize 53100, Türkiye

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These areas, which closely concern and affect the balance, order and living things in nature, often require interdisciplinary studies. The adverse effects of EMF pollution on living things have been a necessary research and discussion topic for scientists in recent years. In this context, individual or joint studies are carried out in the relevant departments of medicine, engineering, agriculture and veterinary faculties and the physics, chemistry and biology departments of the faculty of science (Salama et al. 2010; Zareen et al. 2009).

The biological effects of RF fields on living organisms have been investigated in many studies. In this context, in addition to experimental research on animals, there are also statistical and modelling studies on humans. Although the results show that it poses some risks, some studies show no effect (Birenbaum et al. 2016; Tanner et al. 1969; Youbicier-Simo et al. 1997). Many studies have also investigated the effects of EMF on animals. There are experimental studies and research reviews on experimental animals, chicks, birds, insects and bees (Balmori 2009). As a result of the studies, it has been determined that animals are affected by reproductive abilities, egg development, embryo loss, brain development, etc., with some of these species being affected more (Bastide et al. 2001; Batellier et al. 2008). It is also stated that high-power microwaves cause thermal effects on skin and tissue and stress on the nervous system (Fernie and Reynold 2005). In the living world, migratory birds and fish use the Earth's magnetic field to find their way. On the other hand, bees use Earth's magnetic field for orientation within their environment and communicate with each other. It is thought that EMF signals disrupt this delicate balance since honey bees have lost their ability to find direction (Kirschvink et al. 1997).

Research on bee deaths and colony losses, which increase in parallel with the increase in the use of EMF in Turkey and the world, the mention of the concept of "electromagnetic pollution" among the possible causes in the articles and columns, has led attention to this direction. It is thought that these areas affect honey bees' physiological characteristics and behaviour patterns, especially in the primitive living and production processes (Arney et al. 2016; Favre 2011; Kumar et al. 2011; Sharma and Kumar 2010; Vilic et al. 2017). The mechanism of producing and sensing alternating and electrostatic currents, as well as the tendency of bees to carry a large electrostatic charge related to their body shell characteristics (Eskov and Sapozhnikov 1976), are accompanied by magnetic senses in their abdomen (Liang et al. 2016). In addition, outer body surfaces have semiconductor properties (Eskov and Sapozhnikov 1976). Therefore, charged objects are perceived by bees. The currents induced by artificially produced fields in bees affect the bees and their relationships physiologically (Erdoğan 2019). Abnormal propolization (propolis production), colony loss and colony growth disruption were observed in bees near power transmission lines, especially in humid environments. These effects are generally noteworthy due to the shock currents received from the legs and breasts of the bees (Bindokas et al. 1988).

The magnetic perception sensitivity of honey bees decreases as frequency increases (Kimmel et al. 2007; Shepherd et al. 2019). It has been determined that there is a decrease in the return rate to the hive of the bees, an increase in aggression and significant changes in the honey collection flights of the bees exposed to EMF. In addition, the sounds made by the bees were recorded, and differences were found in the sound recordings of the bees exposed to the EMF (Shepherd et al. 2018).

Bees are reliable indicators of the state of the ecological environment (Zhelyazkova 2012). Significant losses occur in bee colonies due to the contamination of air, soil, water, and nectar, pollen and propolis source plants with chemical and biological substances in the region where the bees are located (Akkaya 2010; Brodschneider et al. 2016; Giray et al. 2007; Kandemir 2007). In addition, bee diseases, viruses, mites, pathogens, application errors, pesticides used in the hive, natural disasters and bee stress factors are among the causes of colony loss. It is also suggested that these reasons, which beekeepers sometimes control and sometimes cannot, collapse the immune system of bees (Bacandritsos et al. 2010). Based on these reasons, losses are gathered under a kind of syndrome called colony collapse disorder (CCD) in beekeeping (Kandemir 2007). In the last 10 years, the effects of electromagnetic fields on bees have been examined. The results of electromagnetic fields on the lives of honey bees, which have vital importance in natural balance and agricultural production, have been the subject of study by many researchers. These effects are covered in the CCD. Although a direct relationship was not detected between EMF and CCD as expected, it has been revealed that it harms bees' lives and honey production (Favre 2011).

Studies on electromagnetic fields in the world are actively carried out by organizations such as the World Health Organization (WHO), the Institute of Electrical and Electronics Engineers (IEEE) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Limit values and regulations for EMR exposure are determined by these organizations (ICNIRP International Commission on Non-Ionizing Radiation Protection 1998). The Information and Communications Technologies

Table 1. Limit values for electric field strengths according to the frequency range (*f = frequency (MHz)) (Official Gazette 2018).

	E – Field Strength (V/m)	
Frequency Range (MHz)	Single Device Limit Value*	Medium Limit Value*
0.010–0.15	19.3	65.25
0.15–1	19.3	65.25
1–10	$19.3/f^{1/2}$	$65.25/f^{1/2}$
10–400	6.2	21
400–789	$0.305\ f^{1/2}$	$1.03f^{1/2}$
790–2000	$0.275\ f^{1/2}$	$0.96f^{1/2}$
2000–94000	12.3	42.93

Authority (ICTA) has become the only authorized institution with the "Regulation on Issuing Security Certificates for Electronic Communication Devices" published in Turkey's Official Gazette in 2009 (Official Gazette 2009). Limit values for electromagnetic fields and power density have been determined and accepted by the WHO and ICNIRP, which is the most reliable authority preferred by many organizations in the international arena (Official Gazette 2009). ICTA has carried out necessary technical and administrative studies to minimize the effects of electromagnetic pollution on human life. The allowable value for the environment in cellular systems has been determined as 70% of the limit values defined by ICNIRP. These values are shown in Table 1. In addition, as additional protection for cellular systems, each device's limits were determined by calculating 20% of the limit values defined by ICNIRP (Official Gazette 2018).

This study aimed to investigate the effects of electromagnetic radiation (EMR) on honey bees' behaviour. The increased prevalence of wireless communication systems in nature means that bees are increasingly exposed to EMR.

Materials and methods

To determine the impact of this exposure, experiments were conducted over two years. In the first year, three groups were created: one exposed to 2.4 GHz Wi-Fi signals, another located under a high voltage line and exposed to Wi-Fi signals, and a control group that was situated away from any EMR sources. Two more groups were added in the second year. During the study, researchers observed the physiological and behavioural effects of EMR on honey bees, including brood area, aggressiveness, cold-casting honeycomb, and colony vitality. The paper presents the EMR limits and experimental setup, followed by the measurement results of the brood area, aggressiveness, cold-casting honeycomb, and colony vitality. Additionally, EMR measurements and weather condition data during the experiment are provided.

Experimental setup

The experiment aimed to investigate the effects of electromagnetic fields (EMF) on honey bees and their products. To achieve this, electronic systems capable of creating EMF were developed and configured in a laboratory environment. Verification measurements were conducted to ensure accuracy, especially for the Wi-Fi system. The EMF transmitter antenna and all other control-related electronic equipment required were arranged as depicted in Figure 1. Following verification in a laboratory setting, the equipment was placed next to the experimental hives outdoors in the field.

The experimental design included a 27 dBm Wi-Fi transmitter, a microcontroller for data collection, and an adaptor to supply energy to the equipment. The Wi-Fi transmitters were placed at a height of 2 meters and about 2 meters away from the hives. The beehives were exposed to the 2.4 GHz frequency band, commonly used for Wi-Fi signals. The microcontroller was set to use UDP (User Datagram Protocol), and the log file was updated with the time whenever random data was sent, enabling the checking of Wi-Fi working time. The experimental setup was positioned near a high-voltage line with a 50 hz low-frequency source. The high voltage line was located approximately 8 m above the ground and approximately 10 m from the beehives.

Data was collected from the hives every 21 days during the colony development period, and the results obtained over three months were evaluated by a team at the end of the season. The Ordu Beekeeping Research Institute analyzed honey yield and several parameters, such as brood area, hive frame number with honey bees, acrimony tendency, and colony vitality. The wintering values of honey bee colonies were also examined in the months following the end of the season.

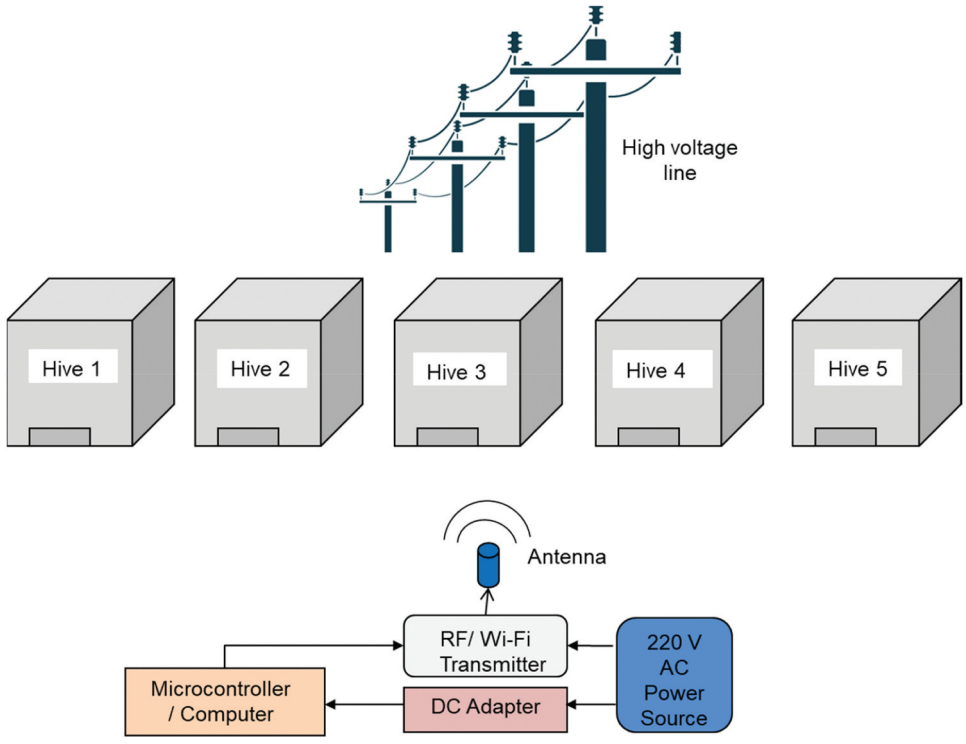


Figure 1. Block diagram of the experimental setup.

Experimental study

The study investigated the physiological and behavioural performance of honey bee colonies under the influence of electromagnetic fields (EMF). The study evaluated parameters such as colony life force, population development, honey yield, wintering ability, and honeycomb processing efficiency. High-frequency EMF measurements from the environment and the hive system were taken using a Narda trademarks SRM 3006 (420 MHz-6 GHz) spectrum analyzer shown in Figure 2(a), while low-frequency field measurements were conducted using a Spectran trademarks NF-5035 (1 hz – 10 MHz) spectrum analyzer shown in Figure 2(b).

The colonies were obtained from the Trabzon region, located in Beşpınar town of Demirözü district of Bayburt Province (40°02'25.8"N, 39°50'51.6"E), an area with vast plant flora and intense beekeeping activities, away from EMF sources.

In 2017 and 2018, local honeybee colonies obtained from the Trabzon region and the same enterprise were used as bee material. The colonies were equalized for environment, genotype, brood area, number of frames with bees, queen age, honey, pollen, etc. In the first year, the colonies were randomly divided into three groups of five: two experimental groups and one control group. In the second year, they were divided into five groups of five: four experimental groups and one control



Figure 2. (a) Narda SRM 3006, and (b) spectran NF-5035 model spectrum analyzers devices.



Figure 3. (a) Group A, (b) group B, and (c) group C hive regions.

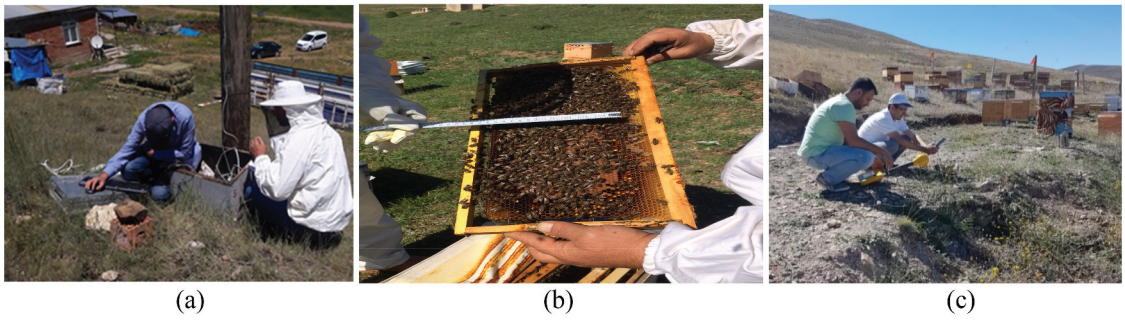


Figure 4. (a) Experimental system setting up, (b) measuring the honeycomb, (c) EMF measurement.

group. The colonies were placed in predetermined areas in Beşpınar town of Demirözü district, as shown in Figure 3(a-c). After allowing the bees to relieve the stress of relocation and to acclimate to the environment, the experiment was conducted with one experimental colony exposed to Wi-Fi signal 24 hours a day (Group A), while the other group was exposed to Wi-Fi signal for 12 hours a day (Group B). Both groups were also placed directly beneath a mid-high voltage line running through the town with a frequency of 50 hz. Figure 4(a) shows the picture from the moment of installation.

The study recorded data on physiological and behavioural characteristics of honey bees in all colonies, such as brood area, number of honey bee frames, honey yield, comb processing efficiency, aggressiveness, wintering ability, and colony vitality. Figure 4(b) shows a picture of the brood area measuring process. The control group (Group C) was situated far from power lines and Wi-Fi transmitters, and electromagnetic field (EMF) levels were much lower compared to the other groups. Additional groups were added in 2018 to reveal the effects of exposure only to a 50 hz area (Group D) and 24-hour Wi-Fi exposure (Group E). The study conducted EMF measurements using low and high-frequency measurement devices. The EMF measurements were made as shown in Figure 4(c).

Measurements

Capped and uncapped brood areas were selected at 21-day intervals to determine the brood efficiency. Since the brood area will develop as an ellipse on the honeycomb, the area in cm^2 was calculated using Equation 1 (Fresnaye and Lensky 1961; Güler 2006).

$$S = \pi . \frac{A}{2} . \frac{a}{2} \quad (1)$$

Where, A denotes the ellipse's long axis, and a denotes the short axis.

To assess the number of hive frames containing honey bees, the study involved systematically inspecting hives at regular intervals. At the outset, each hive was equipped with a standard number of frames, and the presence of honey bees on each frame was recorded. Subsequent inspections, conducted every three weeks, involved carefully examining all frames to count those occupied by honey bees. Any additions or removals of frames were documented, along with their potential impact on bee occupancy. Data from each session were compiled and analyzed to identify trends or significant changes. This methodology ensured accurate and consistent measurement of bee activity across the hive frames while maintaining careful handling of the bees to minimize disturbance.

The scoring method was employed to evaluate bee aggressiveness. The scores given in this scoring method are as follows: aggressive (3 points), manageable (2

points), calm (1 point) and very calm (0 points) (Guzman-Novoa et al. 2003). In measuring the defensive behaviour (aggressiveness) of the colonies, the cover board of the relevant hive was opened at an appropriate time and the behaviour of the colony was observed and scored. This method provided a quantifiable measure of the bees' aggressiveness.

The cold-casting honeycomb processing efficiency was evaluated by measuring the number of honeycomb frames processed by the colonies throughout the honey season. At the beginning of the experiment, the total number of honeycomb frames present in each hive was recorded. The efficiency of honeycomb processing was assessed by comparing the number of processed frames to the total number of frames initially placed in the hives. This information was compiled and analyzed to determine the relative processing efficiency across different experimental groups.

The colony life force was assessed by monitoring and recording instances of colony extinction and queen bee loss throughout the honey season. At each inspection, the number of colonies that had been extinguished (i.e., completely failed or no longer active) and the number of colonies that had lost their queen bees were recorded. The colony life force for each experimental group was then calculated using Equation 2.

$$Colony\ Life\ Force = 1 - \frac{Number\ of\ Extinguished\ Colonies\ +\ Number\ of\ Colonies\ with\ Queen\ Bee\ Loss}{Total\ Number\ of\ Colonies} \quad (2)$$

This formula provides a measure of colony vitality, indicating the proportion of colonies affected by extinction or queen bee loss relative to the total number of colonies. Data were collected periodically throughout the season, and the calculations were updated to reflect the ongoing status of each group. The results were then analyzed to compare the life force across different experimental conditions and assess the impact of electromagnetic fields on colony survival and health.

Weather condition

The data for temperature, humidity, and precipitation during the experimental period were obtained from the General Directorate of Meteorology of the Ministry of Agriculture and Forestry. These data were specifically collected for Beşpınar town, located in the Demirözü district of Bayburt, where the experiments were conducted. Daily temperature, humidity, and precipitation parameters were crucial for understanding the local conditions that could influence the outcomes of the experiments. The data collection focused on the months from June to September for both 2017 and 2018, ensuring a comparative analysis across the years. The obtained meteorological data were further analyzed and represented graphically to observe any notable variations in temperature, humidity, and precipitation during the study period.

Statistical data

In the 2017 honey season, experimental groups in Beşpınar, Demirözü district, Bayburt Province were exposed to different electromagnetic field (EMF) conditions. Group AG was exposed to a 2.4 GHz radio frequency signal (Wi-Fi) for 24 hours daily, while Group BG was exposed for 12 hours daily. Both groups were also situated under a 50 hz high-voltage line. Monitoring was conducted every 21 days to assess hive production and bee behaviour, with data analyzed using one-way ANOVA at a significance level of $p < 0.05$.

In the 2018 season, the study was expanded to include five experimental groups to further investigate the effects of the high-voltage line and Wi-Fi exposure. New groups D and E were added to assess the impact of low-frequency fields and Wi-Fi exposure separately. Consistent methodologies were applied, and new measurements were taken.

Results

Electromagnetic field (EMF) measurements

EMF measurements for hive regions (AG: Group A, BG: Group B, CG: Control Group, DG: Group D, EG: Group E) on three different dates in 2017 and 2018 are given in Figures 5 and 6, respectively. Each measurement is taken for six minutes. The max term in Figures 5 and 6 is used to show maximum data, Max Avg term in the same figures is used to show maximum data of the averaging over the defined number in the Narda SRM 3006. Additionally, the electric field measurements in the low-frequency band (Around 50 hz) for the hive regions are presented in Figure 7. The 420–2600 MHz band range, which we define as the broadband in this

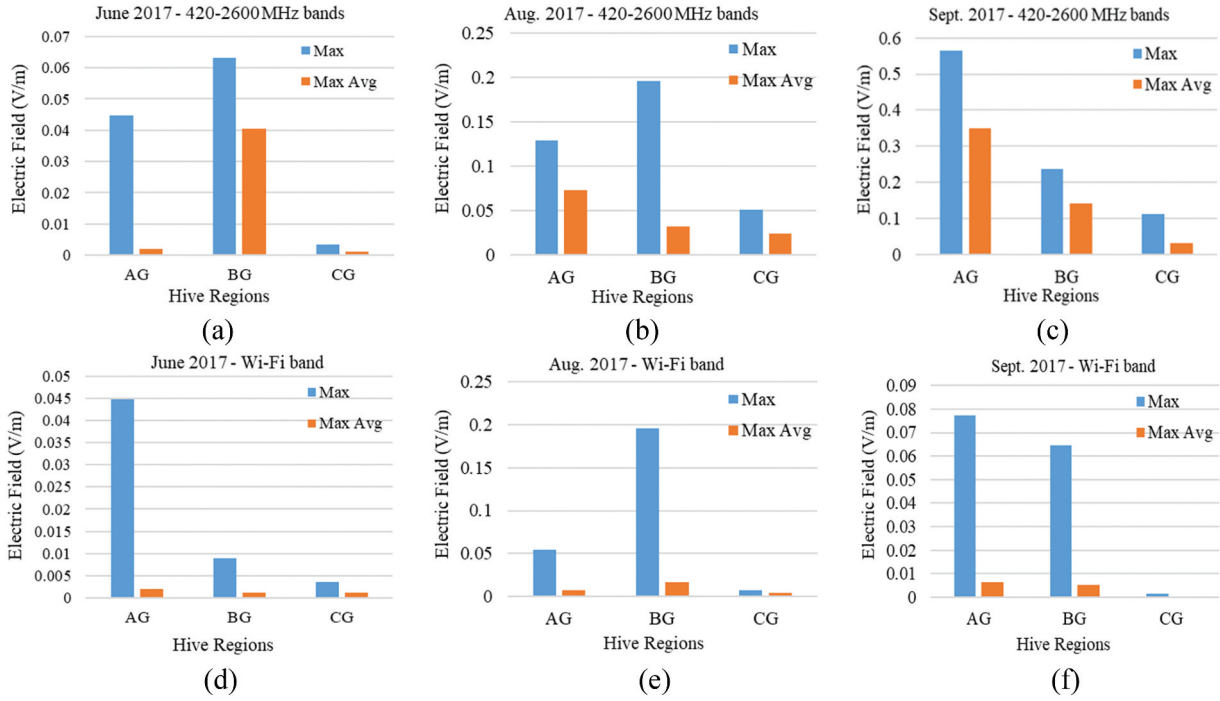


Figure 5. Electric field changes measured in 2017 (a) June, (b) August, (c) September in 420–2600 MHz bands, (d) June, (e) August, and (f) September in the Wi-Fi band.

experiment, and the 2400–2484 MHz band range the WLAN or Wi-Fi band, are shown separately in the graphics.

The EMF densities created by the areas originating from the base stations and transmitters belonging to the operators in the nearby hill of Beşpınar town, where the project area is, and the Wi-Fi station located next to the beehives for the project, have a more significant effect in the A and B regions, as can be seen from Figure 5. Region C, where the control group is located, is in a position where the effect of EMF naturally found is low, as can be seen in Figure 5.

In all measurements, it is seen that the EMF values in the environment where the control group is present are much lower than the EMF values in the territories where the other groups are present. The electric field value in a specific frequency range is measured with Narda SRM-3006. The measurements taken in at least 6 minutes may vary depending on the bandwidth. The data obtained are average measurement values and change over time.

Data of weather condition

The temperature values for the June-September in 2017 and 2018 are shown graphically in Figure 8. The average temperature values for June and July are very close to each other in both years; the temperatures in August and September in 2017 are higher than in the same months of 2018.

The monthly humidity values and the precipitation amounts taken during the experiment period are shown in Figure 9. As shown in Figure 9, the humidity values in 2018 for the mentioned months are higher than in 2017. Beşpınar town, the study area, received more precipitation in June, July, August and September 2018 than in 2017. Most likely, the high amount of humidity in 2018 was due to the high amount of precipitation falling in the study area.

Measurement data

Capped and uncapped brood areas were selected at 21-day intervals to determine the brood efficiency. The obtained brood area values are given in Table 2.

Table 3 provides details on the number of honey bee frames. The initial number of frames placed in the hives at the beginning, the number of frames added and incubated in each group during later periods, and the honey harvested from the hives at the end of the season.

The aggressiveness is the behavioural measurement parameter that shows the stress ratio of the honey bees, and the obtained aggressiveness data are given in Table 4.

The honeycomb processing activity defines the honey bee frames added to the eight frames initially placed in

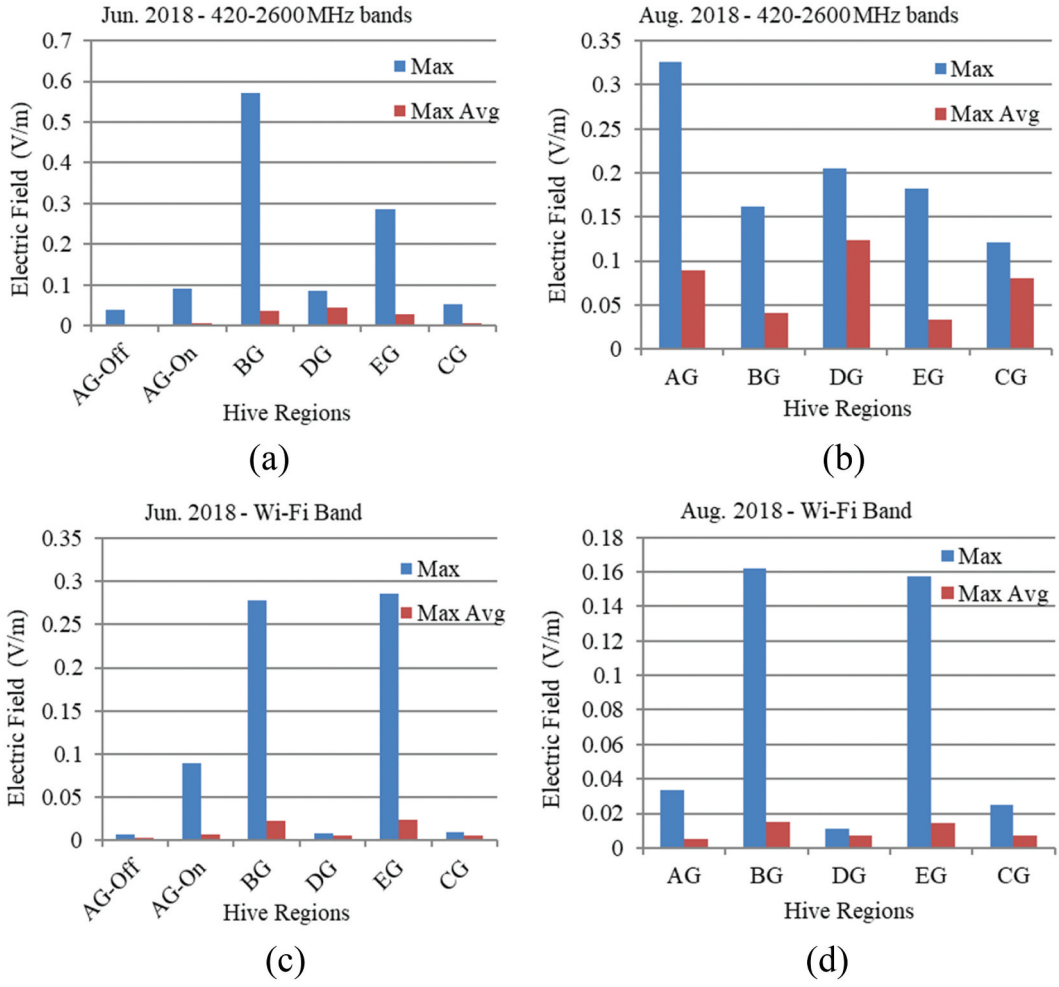


Figure 6. Electric field changes measured in 2018 (a) June, (b) August in 420–2600 MHz, (c) June, and (d) August in the Wi-Fi band.

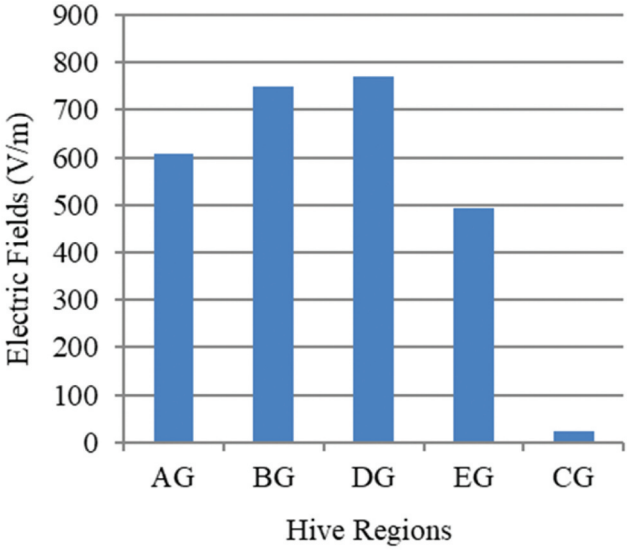


Figure 7. Electric field values in the low-frequency bands.

the hive. The cold-casting honeycomb processing efficiency data obtained are given in Table 5.

Colony life force gives each group the percentage of lost hives due to queen bee loss or honey bee death compared to the remaining hives. The colony life force data are shown in Table 6.

The results indicated no significant difference in brood area between Groups A and B ($p > 0.05$). However, significant differences were observed between the control group (C) and both experimental groups A and B ($p < 0.05$) (see Table 2).

In terms of colony population development, similar results were observed. No significant differences were found between Groups A and B ($p > 0.05$), but significant differences were noted between the control group and the experimental groups ($p < 0.05$) (see Table 3).

Group B, exposed to 12 hours of EMF daily, showed relatively low life force rates, with four colonies losing their queen bees throughout the season. This was reflected in the colony vitality data and shown in Table 6. Group A, exposed to 24 hours of EMF daily, had one colony extinguished at the study's start and demonstrated low-performance values despite a higher

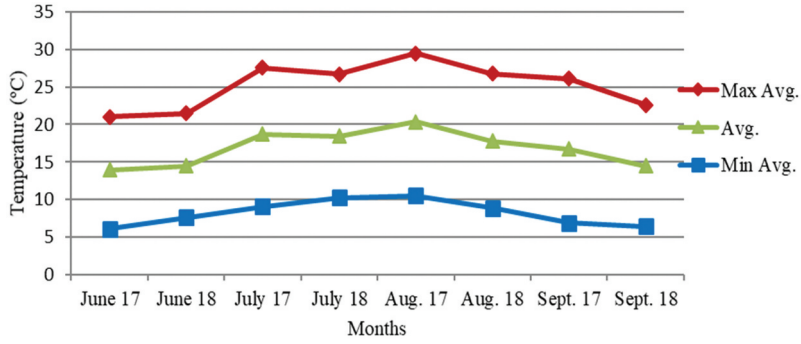


Figure 8. Monthly temperature values of Beşpınar town during the experiment period.

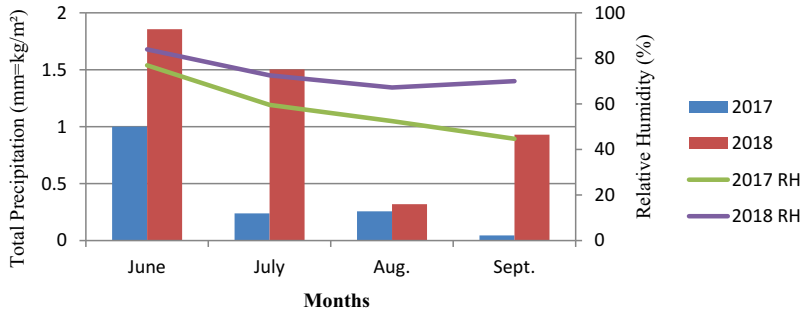


Figure 9. Monthly humidity values and precipitation amounts of Beşpınar town during the experiment period.

Table 2. Brood area (cm^2) data (Q*: Queen bee loss, C*: colony extinguished).

Group A	08-Jun	07-Jun	30-Jun	28-Jun	22-Jul	19-Jul	13-Aug	09-Aug	30-Aug	30-Aug
B C	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
A1	7239	7605	7650	5895	3870	3150	1800	1890	810	Q*
A2	7239	7605	7830	7110	5895	3870	2115	1530	945	855
A3	7239	7605	8820	8325	2880	5760	990	1215	315	1035
A4	7239	7605	10170	6930	6075	3960	2160	720	855	495
A5	C*	7605	—	3960	—	2835	—	C*	—	—
B1	7239	7605	4860	6975	Q*	855	—	Q*	—	—
B2	7239	7605	10872	9000	3240	3825	Q*	1395	—	225
B3	7239	7605	11665	1800	Q*	Q*	—	—	—	—
B4	7239	7605	7200	8460	Q*	5175	—	315	—	Q*
B5	7239	7605	6435	8170	2475	2565	990	900	495	540
C1	7239	7605	7830	11190	4950	8370	2340	5895	2385	3465
C2	7239	7605	12060	11295	7560	7650	4860	6345	3960	2925
C3	7239	7605	11970	9150	6480	6436	3645	5470	2025	3915
C4	7239	7605	13500	11205	6570	7155	3240	5310	1890	2745
C5	7239	7605	10485	9990	6795	6615	3555	4905	1755	3195

Group D -E	07/06/2018	28/06/2018	19/07/2018	09/08/2018	30/08/2018
D1	7605	4770	1395	C*	—
D2	7605	7695	5490	2070	1080
D3	7605	6705	2700	1665	765
D4	7605	Q*	—	—	—
D5	7605	4545	360	Q*	—
E1	7605	9810	3780	765	Q*
E2	7605	7020	1485	2070	900
E3	7605	7875	3015	1485	405
E4	7605	7785	3960	1665	900
E5	7605	2880	Q*	C*	—

Table 3. Numbers of hive frames containing honey bees (Q*: Queen bee loss, C*: colony extinguished).

Group A B-C	08-Jun 2017	07-Jun 2018	30-Jun 2017	28-Jun 2018	22-Jul 2017	19-Jul 2018	13-Aug 2017	09-Aug 2018	30-Aug 2017	30-Aug 2018	Honey yield 2017 (kg)	Honey yield 2018 (kg)
A1	8	8	11	9	8	6	5	3	5	Q*	—	—
A2	8	8	9	9	6	7	5	4	4	3	—	—
A3	8	8	11	9	7	6	5	4	5	3	—	—
A4	8	8	11	9	9	5	5	2	4	2	—	—
A5	C*	8	—	9	—	4	—	C*	—	—	—	—
B1	8	8	10	9	Q*	7	—	Q*	—	—	—	—
B2	8	8	11	9	7	7	Q*	7	—	2	—	—
B3	8	8	11	9	Q*	Q*	—	—	—	—	—	—
B4	8	8	9	9	Q*	6	—	2	—	Q*	—	—
B5	8	8	7	9	8	6	8	3	8	3	—	—
C1	8	9	13	13	15	14	15	14	15	6	9	6
C2	8	9	15	13	17	16	17	16	17	5	10	8
C3	8	9	16	13	18	15	18	16	18	6	13	7
C4	8	9	18	13	20	15	20	15	20	6	15	7,5
C5	8	9	15	13	18	16	18	16	18	6	12	8

Group D	07/06/2018	28/06/2018	19/07/2018	09/08/2018	30/08/2018	Honey yield (kg)
D1	8	5	3	C*	—-	—
D2	8	6	5	4	3	—
D3	8	7	6	4	3	—
D4	8	Q*	—	—	—	—
D5	8	6	2	Q*	—	—
E1	8	9	5	3	Q*	0
E2	8	9	6	4	3	0
E3	8	9	7	3	2	0
E4	8	9	6	4	3	0
E5	8	3	Q*	—	—	0

Table 4. Aggressiveness data (Q*: Queen bee loss, C*: colony extinguished, 3: aggressive, 2: manageable, 1: calm, 0: very calm).

Group A	08-Jun	07-Jun	30-Jun	28-Jun	22-Jul	19-Jul	13-Aug	09-Aug	30-Aug	30-Aug
B – C	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
A1	0	0	1	1	2	2	3	3	3	Q*
A2	0	0	2	1	2	2	3	3	3	3
A3	0	0	2	1	2	3	3	3	3	3
A4	0	0	1	1	2	3	3	3	3	3
A5	C*	0	—	1	—	3	—	C*	—	—
B1	0	0	2	2	Q*	3	—	Q*	—	—
B2	0	0	1	2	3	2	Q*	3	—	3
B3	0	0	2	3	Q*	Q*	—	—	—	—
B4	0	0	3	2	Q*	2	—	3	—	Q*
B5	0	0	2	2	3	3	3	3	3	3
C1	0	0	0	1	0	1	1	1	1	2
C2	0	0	0	1	0	1	1	1	1	2
C3	0	0	0	1	0	1	1	1	1	2
C4	0	0	0	1	0	1	1	1	1	2
C5	0	0	0	1	0	1	1	1	1	2

Group D E	07/06/2018	28/06/2018	19/07/2018	09/08/2018	30/08/2018
D1	0	2	3	3	—
D2	0	2	2	3	3
D3	0	1	2	3	3
D4	0	3	—	—	—
D5	0	2	3	—	—
E1	0	1	3	3	—
E2	0	2	3	3	3
E3	0	1	2	3	3
E4	0	2	2	3	3
E5	0	3	—	—	—

life force rate compared to Group B. In contrast, the control group (C) maintained a 100% colony life force, with no issues in beekeeping (see Table 6).

Bee aggressiveness, measured by counting stings on a tennis ball, was lowest in the control group (C) at levels 0–1. In Groups A and B, aggressiveness increased to levels 2–3, with Group B consistently showing higher aggressiveness than Group A. Statistically significant differences in aggressiveness were found between the control group and both experimental groups ($p < 0.05$),

Table 5. Cold-casting honeycomb processing activity data.

Processed Hive	2017	2018	Processed Hive	2017	2018	Processed Hive	2017	2018	Processed Hive	2018	Processed Hive	2018
A1	3	1	B1	2	1	C1	7	6	D1	0	E1	1
A2	1	1	B2	3	1	C2	9	8	D2	0	E2	1
A3	3	1	B3	3	1	C3	10	8	D3	0	E3	1
A4	3	1	B4	1	1	C4	12	7	D4	0	E4	1
A5	0	1	B5	0	1	C5	10	8	D5	0	E5	0

Table 6. Colony vitality data.

Groups	Extinguished Colony 2017	Extinguished Colony 2018	Queen bee loss 2017	Queen bee loss 2018	Colony Life Force (%) 2017	Colony Life Force (%) 2018
A (24h)	1	1	-	1	80	60
B (12h)	-	-	4	3	20	40
C (Control Group)	-	-	-	-	100	100
D (50 hz)		1		2		40
E (Wi-Fi)		-		2		60

although no difference was observed between Groups A and B ($p > 0.05$) (see Table 4).

Honeycomb processing efficiency was higher in Group C compared to Groups A and B, with Group C producing 9 kg to 15 kg of honey per hive. This is supported by the cold-casting honeycomb processing activity data (see Table 5). Experimental Groups A and B did not produce honey, and samples were obtained from honey bee food. EMF measurements showed a peak strength of 0.54 V/m in the broadband range and 0.2 V/m in the Wi-Fi band. All values were below ICTA standard limits, but EMF densities were higher in Groups A and B compared to Group C.

Results from 2018 showed no significant differences in brood area among Groups A, B, D, and E ($p > 0.05$), but significant differences were noted between the control group (C) and all other groups ($p < 0.05$) (see Table 2). Colony population development mirrored these findings, with no significant differences among the experimental groups ($p > 0.05$) but significant differences between the control group and the experimental groups ($p < 0.05$) (see Table 3).

Group B experienced decreased colony survival rates due to queen bee losses (see Table 6), while Group A had no losses but no brood or honey production. Groups D and E, exposed to the high-voltage field and Wi-Fi respectively, also faced queen bee losses and colony extinctions at various times during the season (see Table 6). Aggressiveness levels increased in all experimental groups, with Group E showing the highest levels. Significant differences in aggressiveness were found between the control group and the experimental groups ($p < 0.05$), though no differences were observed among the experimental groups ($p > 0.05$) (see Table 4).

Honeycomb processing efficiency was notably higher in Group C, with minimal processing in Groups A, B, and E, and none in Group D (see Table 5). Colony life force was 100% in Group C, 60% in Groups A and E, and 40% in Groups B and D (see Table 6). EMF measurements indicated peak values of 0.57 V/m in the broadband range and 0.29 V/m in the Wi-Fi band (see Figure 8). All values remained below ICTA standards, with higher EMF activity in Groups A, B, D, and E compared to Group C (see Figures 8 and 9).

Honey production in the control group was 6 kg to 8 kg, lower than the previous year. The low-frequency field measurements in Group C were lower than in other regions, indicating the lowest EMF spread in that area.

Discussion

The results obtained in 2017 indicate that in Group B colonies exposed to EMF for 12 hours daily, the varying electromagnetic field caused stress in honey bees starting from the first month, leading to decreased colony vitality due to queen bee losses. In Group A colonies, which were exposed to EMF continuously for 24 hours, honey bees appeared to adapt to living under constant field exposure. However, despite this adaptation, neither brood production efficiency nor honey production was observed, likely due to the persistent stress caused by electromagnetic fields.

The 2018 experiment results mirrored those of 2017, reinforcing the conclusion that EMF intensity adversely affects honey bees. Key impacts include reduced colony vitality, lower honeycomb processing efficiency, increased aggressiveness, and absence of honey

production. The high stress levels induced by EMFs seem to be the primary driver of these effects. Notably, no honey production in the experimental groups precludes evaluating EMF's impact on honey quality. Additionally, observations from Groups D and E in 2018 suggest that high-voltage lines with low-frequency fields have even more detrimental effects on honey bees.

Lower yields in honeycomb processing and honey harvest were observed in the control group during the 2018 season compared to 2017. This reduction is attributed to unfavourable weather conditions, including lower temperatures, higher humidity, and more precipitation during the 2018 beekeeping season.

The findings of this study align closely with earlier research. For instance, one study observed that EMR disrupts pollinator dynamics, reducing the abundance of certain species, which supports the conclusion that electromagnetic exposure has a detrimental effect on honey bees (Lázaro et al. 2016). Similarly, studies documented how EMR disrupts metabolic and behavioural processes in honey bees, with the severity of effects linked to the intensity of exposure (Greenberg et al. 1981; Kumar et al. 2013; Odemer and Odemer 2019). These studies bolster our conclusion that prolonged exposure to electromagnetic fields can cause significant colony stress, reducing productivity and vitality.

In alignment with this study, previous research has shown that combined stressors, such as pesticides and electromagnetic fields, exacerbate adverse effects on bee health. For instance, colonies exposed to multi-stress conditions showed severe health declines, with only one colony surviving by the end of the experiment (Lupi et al. 2021). Similarly, studies have demonstrated that exposure to electric fields at 50 hz causes significant behavioural changes in honey bees, including reduced activity and altered biochemical parameters like antioxidant enzyme activity (Migdał et al. 2020, 2021). Furthermore, honey bees' natural sensitivity to electromagnetic fields, which they use for navigation and communication, makes them particularly vulnerable to EMR (Greggers et al. 2013).

Other studies emphasize the ecological risks of EMFs, particularly from 5 G, calling for immediate monitoring and stricter regulations to mitigate these effects (Levitt et al. 2022; Thill et al. 2024). EMR is also identified as an additional stressor contributing to global insect biodiversity loss, advocating for precautionary approaches to new technology deployment (Balmori 2021). Wi-Fi EMR has been shown to impair honeybee memory and behaviour, potentially contributing to colony collapse disorder (Lopatina et al. 2019). Colonies closer to cell phone towers experienced reduced flight activity, with foraging behaviour peaking at greater distances (Taye et al. 2017). These findings, along with the current study, collectively indicate that EMF is a significant stressor on honey bee populations, directly impacting their health, behaviour, and ecological roles.

The present study complements and reinforces existing research by offering field-based evidence on the impact of high-voltage transmission lines and electromagnetic radiation on honey bee colonies. In particular, the observed stress effects and diminished productivity confirm trends identified in other studies, underscoring the urgent need for further investigation and mitigation measures to protect honey bees and their critical role in ecosystems.

Conclusion

In this study, the effects of electromagnetic radiation (EMR) on honey bees were investigated using a carefully designed experimental setup. A high-frequency EMF source was generated using a high-power Wi-Fi router, while a low-frequency EMF source was derived directly from high-voltage power lines. A significant difference was observed between EMF-exposed beehives (experimental groups) and non-exposed hives (control groups), with the control groups showing markedly better outcomes.

No honey yield was recorded in the EMF-exposed hives. Additionally, while the control group exhibited low levels of aggressiveness, the experimental groups displayed heightened aggression. Similar adverse impacts were noted in the number of hive frames containing honey bees, cold-casting honeycomb processing activity, and colony vitality parameters.

Based on the collected data, it is evident that EMFs have detrimental effects on honey bees. The stronger impact of high-voltage lines suggests that this factor should be carefully considered when selecting hive placement sites, particularly in regions with significant electromagnetic activity.

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