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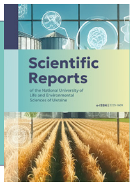

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IInfluence of electromagnetic radiation on the growth and productivity of agricultural crops in the agro-industrial complex

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Abstract. The purpose of this study was to determine the characteristics of the effect of different levels of electromagnetic radiation on biometric indicators and yields of major agricultural crops, such as wheat, corn, and soybeans. The study was conducted on samples of wheat, corn, and soybeans grown

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in agroclimatic conditions of the Kharkiv region. The cultures were exposed to radiation in the range from 50 to 200 Hz using special equipment. The main measurements included analysis of biometric characteristics: plant height, leaf count, root system mass, morbidity index, and overall yield. The results showed that low levels of electromagnetic radiation stimulated wheat growth, increasing yields by 12-15%, and also increasing the number of leaves by 10-12%. For corn, the effect of radiation was positive, in particular, there was an increase in the mass of the root system by 18% and a decrease in the morbidity index by 15%. Soybeans showed the greatest response to radiation, with an increase in growth by 19.23%, root system mass by 25%, and a decrease in the incidence index by 15-20%. The results of the study indicate the potential for using controlled electromagnetic radiation to increase the productivity of individual crops, especially soybeans in difficult agroclimatic conditions. The data obtained can be useful for the development of new technologies in the field of agriculture aimed at increasing yields, contributing to the achievement of Sustainable Development Goals, and providing a more environmentally friendly approach to increasing crop yields and sustainability

Keywords: biometric indicators; yield; agrotechnical factors; plant productivity

Introduction

In the modern agro-industrial complex, the issue of increasing crop productivity is becoming increasingly relevant due to global climate change, population growth, and the need to ensure food security. One of the new technological strategies that attracts attention is the use of electromagnetic radiation to stimulate plant growth. The problems associated with optimising growing conditions are more urgent than ever since the efficiency of agricultural production directly depends on many agronomic and environmental factors. Despite the research that has already been conducted in this area, there are still many unexplored aspects of the impact of electromagnetic radiation on agricultural crops. The results of work conducted by various authors indicate that the influence of the electromagnetic field can vary depending on the type of crop, the level of irradiation, and the specific features of agroclimatic conditions.

Scientific research in the field of light radiation exposure to plants is important for understanding the biophysical processes occurring in the plant body. The main areas under study in this sphere are represented by the papers of individual foreign researchers. The examination of this phenomenon is especially important for countries with agroclimatic conditions similar to Ukraine, as it can help to find new approaches to integrating modern technologies into traditional agriculture. The crops considered, such as wheat, corn, and soybeans, show different sensitivity to changes in the electromagnetic field, which requires more in-depth study. They are the main agricultural products that ensure food security, promote economic development, and form the country's export potential.

R. Dennis *et al.* (2021) investigated the effect of pulsing electromagnetic fields (PEMF) on seed germination. The study showed that certain levels of electromagnetic exposure can stimulate germination, while excessive exposure can have a negative effect. This highlights the importance of optimising impact parameters to achieve maximum results in agricultural production. The results of the study open up new prospects for the use of PEMF in agronomy, showing how electromagnetic fields can be an effective tool for improving seed germination processes.

Similarly, L. Popescu & A.S. Safta (2021) in their study analysed the possible effects of electromagnetic waves emitted from various sources on agricultural production. The authors emphasised the growing interest in assessing the impact of these waves on plant growth and yield, especially in the context of technological development in the agricultural sector. They considered both the positive and negative effects of exposure to electromagnetic waves, noting that some frequencies can promote growth, while others can disrupt biological processes.

H.G.J. Snell *et al*. (2021) investigated the use of electromagnetic fields in precision agricultural practice using the example of corn to determine the dry matter content. The results showed the possibility of improving the accuracy and speed of measuremets, which, in turn, can help agronomists better plan fertiliser application and field management.

S. Ayesha *et al*. (2023) similarly considered the mechanisms of influence of electromagnetic fields on sustainable plant production and food security. The study presented results that confirm that electromagnetic fields can promote the development of the root system, increase resistance to stressful conditions, and improve the overall condition of plants.

It is also important to consider the contribution of Ukrainian scientists to the study and examination of the influence of electromagnetic radiation on agricultural crops, which adapt methods and results to the specific conditions of Ukraine's agricultural climate.

O. Pankova *et al*. (2021) examined in detail the effects of electromagnetic radiation on plants, focusing on the physiological responses of plants to electromagnetic fields. The monograph has become a source for further work in this area, providing experimental data that support the possibility of using electromagnetic fields to improve agronomic practices.

L. Haidai (2019) considered the specific features of the formation of productivity and functioning of the legume-rhizobial symbiosis of common beans in the conditions of the Right-Bank Forest-Steppe of Ukraine. The study focused on the importance of rhizobial bacteria for improving the nitrogen nutrition of plants, which, in turn, has a positive effect on their productivity. The author examined the influence of various factors, such as soil conditions and climatic features, on the development of symbiosis, emphasising the role of such relationships in increasing the yield of legumes.

Evidently, the amount of research in this area is quite substantial, which indicates the relevance of the topic. Problems related to the impact of light conditions on plant growth and productivity are becoming important due to the need to improve the efficiency of the agricultural sector, which is especially important for agricultural countries such as Ukraine. The aim of this study was to determine the optimal parameters of electromagnetic exposure for improving biometric indicators of plants, such as height, number of leaves, root system mass, and overall yield, as well as to assess the potential benefits of using electromagnetic radiation in the modern agro-industrial complex.

Materials and Methods

The study was conducted during one growing season, which is optimal for monitoring the growth and productivity of agricultural crops. The experiment began with the spring sowing campaign of 2024, which took place in April and lasted until the harvest in the fall, in September-October. The total duration of the study was 5-6 months, which allowed fully assessing the effect of electromagnetic radiation on the growth and development of the studied crops. Seeds of agricultural crops were exposed to electromagnetic radiation. Irradiation was conducted before sowing, which allowed creating a stimulating effect on the initial phases of plant development. After the irradiation procedure, the seeds were planted in prepared areas in the field.

The list of agricultural crops that were used in the experiment included wheat (*triticum aestivum*), corn (*sea mays*), and soy (*glycine Mach*). Wheat and corn are the main crops for the agro-industrial complex of the Kharkiv region, as they are of great importance for ensuring food security and forming the country's export potential. Soy, in turn, as of 2024, is not a widespread crop in the agro-industrial complex of the region but its cultivation is promising. Therefore, in particular, for soybeans, the goal was to examine the effects of electromagnetic radiation to improve its productivity and promote the expansion of this crop in the region. For the experiment, the Kharkiv region was chosen, where the climatic conditions differ from the southern regions of Ukraine, in particular, with a lower level of sunlight. This helps investigate the effect of electromagnetic radiation in conditions close to typical for the northern agricultural zones of the country. Kharkiv region is characterised by a temperate continental climate with sufficient precipitation and cooler summers, which avoids overheating of plants and creates more favourable conditions for analysing the effects of electromagnetic radiation on their development. This choice of location is also justified by the fact that the results of the study will be relevant for other agricultural regions of Ukraine with similar climatic and agronomic characteristics, which will contribute to the integration of electromagnetic stimulation technologies throughout the country. In the study, various methods of measuring plant biometrics were used to assess the effect of electromagnetic radiation on crop growth and productivity, in particular, plant height, leaf count, root system mass, and total yield.

Plant height measurement was performed using an ultrasonic plant height meter (model: LIDAR plant Height Meter, manufacturer: Yantai Maohai Intelligent Technology Co., Ltd., China, 2020). The device allows accurately determining the height of plants in the field due to laser technology, which ensures high accuracy and speed of measurement. The number of leaves was established manually, by counting it and determining the arithmetic mean of this value. The results were compared with data obtained using an optical photometer for sheet surface analysis (model: Leaf Area Meter, manufacturer: CID Bio-Science, USA, 2019). This device accurately measures the area of the leaf surface, which is important for assessing the photosynthetic activity of plants. The mass of the root system was calculated using analogue weighing platforms (model: Wittmann AG, manufacturer: Wittmann, Germany, 2021). After removing the root system from the soil, it was cleaned and measured to determine the mass of the roots, which is an important biometric indicator. Yield assessment was conducted using an electronic crop analyser (model: Harvestmaster GrainGage, manufacturer: Crop Test, USA, 2020). This device quickly and accurately measures the mass and volume of the crop, allowing for a complete picture of crop productivity.

The study on electromagnetic radiation was conducted under controlled conditions of a field experiment, which allowed bringing the conditions of exposure to the electromagnetic field as close as possible to real field conditions where crops are grown. However, the irradiation process itself was conducted in a specially equipped enclosed space on the basis of the agronomic station of the Kharkiv National University, where all the necessary conditions were created to control the radiation parameters. Electromagnetic radiation was provided by an alternating current generator (model: Elma EMF 2020, manufacturer: Elma GmbH, Germany, 2019). The generator provided regulated radiation in a given frequency and power range. Experimental settings allowed varying the frequency and intensity of radiation within a certain range, examining the effect of various parameters of the electromagnetic field on plant growth.

Plants were irradiated at different stages of vegetation to assess the effect of the electromagnetic field on various aspects of growth and development. Irradiation was conducted in several variants:

1. Periodic exposure. Irradiation was conducted several times a week during certain periods of crop development (for example, at the stage of germination, during flowering and at the stage of fruit formation).

2. Constant exposure. Irradiation was conducted without interruptions throughout the growing season to determine the cumulative effect of exposure to an electromagnetic field.

The electromagnetic field on plants was affected by two main types of installations. Inductive coils located around the plants were used to provide a direct effect on plants, creating an alternating electromagnetic field. The plants were installed inside the coils, where they were irradiated according to the principle of alternating field induction. Additionally, the technique of creating an electric field by applying a potential between two electrodes was used, which provided contact with the root system of plants. This method is designed to examine the effect of electrical properties on biological processes, in particular, to stimulate the growth of the root system and accelerate water supply.

Monitoring of the parameters of electromagnetic radiation was conducted in the laboratory using special sensors for measuring voltage, current, and electromagnetic field, which allowed maintaining the stability and accuracy of the experiment. The experiment used an alternating current generator to ensure the accuracy and stability of electromagnetic radiation which helped to control the frequency and intensity of radiation. The generator allowed setting frequencies in the range of 50-200 Hz, which is critical for assessing the influence of various electromagnetic fields on plant growth and productivity.

The voltage applied to the generator electrodes could vary according to the requirements of the experiment, which provided the required electric field intensity. During the experiment, radiation parameters were regularly monitored to avoid fluctuations in frequency and intensity values that could affect the results. Before starting the experiment, the equipment was calibrated to ensure the accuracy of the measurements and the correspondence between the set values and the actual radiation parameters. Before starting calibration, all elements of the system, including the generator, electrodes, and measuring instruments, were checked to ensure that there was no mechanical damage and that the connection was correct. The generator was tuned to the initial frequency (50 Hz) and the voltage that was planned for the experiment. This provided a starting point for further calibration. Adjusting the generator settings may include changing the voltage or frequency to achieve the required electric field level. All measurement results were recorded in the calibration protocol. In particular, the initial settings of the generator, the obtained values of the electric field and the adjustments made were indicated.

Calibration was repeated on a regular basis to ensure the stability and accuracy of the experiment, especially before each serious stage of the experiment. The selected radiation parameters-frequencies of 50, 100, 150, and 200 Hz – are based on studies conducted to assess the effect of electromagnetic fields on plant biological processes (Petrovskyi & Volkov, 2011; Christie *et al.*, 2012). Previous studies have shown that variable fields in this range can stimulate plant growth, activating photosynthetic processes and improving metabolism.

Thus, the parameters of the frequency and intensity of electromagnetic radiation were selected based on previous studies confirming their potential to stimulate the growth and productivity of agricultural crops. Several basic analysis approaches are usually used to assess the effect of electromagnetic radiation on crop growth and productivity (Chalker-Scott, 1999; Sviren *et al.*, 2016). Biometric indicators (plant height, number of leaves, root system mass, total yield, etc.) are measured, and then, these values are compared in the control and experimental groups. Basic parameters for assessing the impact of electromagnetic radiation:

1. Plant height (H) – measured in centimetres from the soil surface to the top of the plant.

2. Number of leaves (N) – the total number of leaves on each plant is counted.

3. Root system Mass (M_e) – determined by removing the root system after harvesting the plant and weighing it.

4. Yield (Y) – defined as the total amount of yield per unit area (tonnes/ha).

The growth index (GI) was calculated using the Formula (1):

$$GI = \frac{H_1}{H_0} \cdot 100\%, \quad (1)$$

where H_0 – the average plant height in the control group; H_1 – the average plant height in the experimental group.

This allows comparing the average plant growth in the experimental group with the control plants and evaluating the effectiveness of radiation exposure. The following Formula (2) was used to calculate the root system development index:

$$IRK = \frac{M_1}{M_0} \cdot 100\%, \quad (2)$$

where M_0 – the average root mass in the control group; M_1 – the average root mass in the experimental group.

This formula estimates how much the mass of the root system has changed as a result of exposure to electromagnetic radiation. Plant disease is also one of the most critical factors that negatively affect their yield and product quality. Pathogens can substantially reduce plant growth and development by disrupting photosynthesis, transpiration, and nutrient absorption. In the current experiment, resistance to diseases such as pyrenophorosis (on wheat), multicoloured mould (on soy), and corn rot (Pinchuk *et al.*, 2018).

The Bobby scale was used to assess the degree of damage, which allows quantifying the spread of the disease on a five-point scale. This technique provides convenience in the field and allows quickly assessing the degree of damage at different stages of plant development. Measurements were performed on plants of the control and experimental groups, followed by data analysis to calculate the overall plant resistance to diseases. The Bobby scale includes the following categories:

- 1 point – healthy plants, no visible symptoms of the lesion;
- 2 points – weak lesion covering approximately 10% of the plant area;
- 3 points – moderate damage covering approximately 25% of the area;
- 4 points – substantial lesion that affects 50% of the plant;
- 5 points – severe lesion covering more than 75% of the plant.

The defeat index was calculated using the following Formula (3):

$$I = \frac{\sum(a \cdot b)}{N \cdot K} \cdot 100\%, \quad (3)$$

where I – the lesion index as a percentage; a – the number of plants with a certain degree of damage; b – the lesion score according to the scale; N – the total number of plants examined; K – the maximum possible lesion score (in this case, 5).

This index allows quantifying the level of disease damage and using these data for further agrotechnical decisions to increase plant resistance and reduce crop losses. For each crop (wheat, corn, soy), the results can be summarised separately. Changes in biometric characteristics after treatment are evaluated for each plant. These results are then compared to determine the greatest impact on a particular culture. In the course of conducting this study, all ethical standards specified in legislative acts were observed (Convention "On Biological Diversity", 1992; Law of Ukraine No. 1264-XII, 2024). All research practices related to the collection of vegetation data were conducted in accordance with the Principles of Sustainable Use of Natural Resources and Protection of Biodiversity.

Results

A study conducted during one growing season in the Kharkiv region showed a substantial effect of electromagnetic radiation on the growth and development of agricultural crops, in particular, wheat, corn, and soybeans. According to the results of the experiment, it was determined that radiation has a positive effect on all the studied crops but the most impressive changes were observed in soybeans which allows considering the use of electromagnetic radiation as the most relevant for this crop.

The temperature regime was one of the critical parameters that was monitored throughout the experiment. During the growing season, the air temperature ranged from 18 to 25°C, which is optimal for most crops, including wheat and corn (Zymaroieva, 2019). However, for soybeans, which are more sensitive to temperature fluctuations, these indicators may have been less favourable, which is especially important to consider when interpreting the results of exposure to electromagnetic radiation.

Air humidity also varied throughout the experiment, in particular, during the period of plant irradiation, it was in the range of 60 to 80%. This provided stable conditions for plant development and minimised the impact of arid conditions on the results of the experiment. According to scientific guidelines, humidity control is an important factor in maintaining proper plant development when exposed to external factors such as electromagnetic radiation (Pankova *et al.*, 2021).

After the irradiation was completed, the seeds were planted on experimental plots in compliance with agrotechnical standards, including the standard sowing scheme for each crop. It is important to emphasise that the irradiated seeds grew under conditions similar to the control samples, allowing the comparison of the results without additional changes in external conditions. The data in Table 1 show how the height of the plants participating in the experiment changed during 6 weeks of exposure.

Table 1. *Changes in plant height under the influence of electromagnetic radiation during the growing season*

Crop	Growing season	Control group (cm)	Experimental group (cm)
Wheat	2 weeks	25	30
	4 weeks	45	52
	6 weeks	60	68
Corn	2 weeks	40	45
	4 weeks	90	100
	6 weeks	140	150
Soybeans	2 weeks	20	26
	4 weeks	35	42
	6 weeks	52	62

Source: compiled by the authors

The data show changes in plant height under the influence of electromagnetic radiation during the growing season. The results obtained allowed calculating such an important indicator as GI. The results for each of the crops were considered separately to analyse the growth index at 6 weeks. GI for wheat was calculated based on the average plant height in the control (60 cm) and experimental groups (68 cm):

$$\text{GI wheat} = \frac{68}{60} \cdot 100\% \approx 113.33\%.$$

This indicator indicates moderate stimulation of wheat growth in conditions of electromagnetic radiation. For corn, the average plant height in the control group was 140 cm, and in the experimental group – 150 cm:

$$\text{GI corn} = \frac{150}{140} \cdot 100\% \approx 107.14\%.$$

This result indicates some improvement in corn growth, although the effect was less pronounced compared to other crops. The average height of soybean plants in the control group was 52 cm, and in the experimental group – 62 cm:

$$\text{GI soybean} = \frac{62}{52} \cdot 100\% \approx 119.23\%.$$

High GI in soybeans indicates substantial growth stimulation under the influence of electromagnetic radiation. Thus, the results of the Growth Index obtained at week 6 of the experiment demonstrate a positive effect of electromagnetic radiation on plant development. Wheat showed a GI of 113.33%, indicating moderate stimulus. Corn, with an index of 107.14%, showed some improvement, although less pronounced. The highest index of 119.23% was recorded in soybeans, which indicates a substantial stimulation of its growth.

Table 2 shows data on the mass of the root system in grams for control and experimental groups at different stages of vegetation (after 2, 4, and 6 weeks). These indicators allow assessing the effect of electromagnetic radiation on the development of the root system of each crop and determining the potential to increase their stability and productivity under experimental conditions.

Table 2. *Dynamics of changes in the mass of the root system under the influence of electromagnetic radiation*

Crop	Vegetation period	Control group (g)	Experimental group (g)
Wheat	2 weeks	5	6
	4 weeks	10	12
	6 weeks	15	18
Corn	2 weeks	7	8
	4 weeks	18	20
	6 weeks	25	28
Soybeans	2 weeks	3	4
	4 weeks	6	8
	6 weeks	8	10

Source: compiled by the authors

The root system mass index (RSMI) was calculated to analyse the effect of electromagnetic radiation on root system development throughout the experiment. Next, the above index was calculated for the sixth week of vegetation, which was the most substantial since it helped to assess future trends. For wheat:

1. Average root weight in the control group (M_0): 15 g.

2. Average root weight in the experimental group (M_1): 18 g:

$$\text{RSMI wheat} = \frac{18}{15} \cdot 100\% \approx 120\%.$$

This result indicates that the mass of the wheat root system in the experimental group is 20% higher than in the control group, which indicates a positive effect of electromagnetic radiation. For corn:

1. Average root weight in the control group: 25 g.

2. Average root weight in the experimental group: 28 g:

$$\text{RSMI corn} = \frac{28}{25} \cdot 100\% \approx 112\%.$$

Consequently, the mass index of the corn root system in the experimental group is 12% higher compared to the control variant. This is a positive result. For soybeans:

1. Average root weight in the control group: 8 g.

2. Average root weight in the experimental group: 10 g:

$$\text{RSMI soybean} = \frac{10}{8} \cdot 100\% \approx 125\%.$$

This indicator indicates that the mass of the soybean root system in the experimental group exceeds the control by 25%, which confirms the effectiveness of exposure to electromagnetic radiation. Consequently, the results obtained indicate an overall increase in the mass of the root system of all three crops in the experimental groups. Wheat, corn, and soybeans show a marked improvement in root system development under the influence of radiation of varying degrees. The increase in root system mass observed in the experimental groups indicates an increased ability of plants to absorb water and nutrients from the soil. This is a viral factor for plant growth. The generalised results of biometric indicators of plants under the influence of electromagnetic radiation are presented in Table 3.

Table 3. *Specific effect of electromagnetic radiation on biometric indicators (in %)*

Crop	Indicator	Control group	Experimental group
Wheat	Plant height	78	90
	Root system mass	15	18
Corn	Plant height	170	185
	Root system mass	25	28
Soybeans	Plant height	52	62
	Root system mass	8	10

Source: compiled by the authors

The results of the experiment showed that in the control group of wheat, the average height of plants was 78 cm, while in the group that was exposed to electromagnetic radiation, plants grew to 90 cm. This indicates a 15.38% increase in plant height under the influence of radiation. Similarly, an increase in the mass of the root system was observed: in the control group it was 15 g, and in the experimental group – 18 g, which confirms an improvement in the root structure and overall viability of plants (an increase of 20%).

For corn, a positive effect of electromagnetic radiation was also observed. In the control group, the average plant height was 170 cm, while in the experimental group, it was 185 cm, which shows a growth of 8.82%. This may indicate the stimulation of plant growth under the influence of radiation, which is an important factor for optimising the use of land resources and increasing yields.

As for the mass of the root system, it increased from 25 g in the control group to 28 g in the experimental group, which corresponds to an increase of 12%. The change in yield for corn was 8.33%, which also confirms the positive effect of electromagnetic radiation on the overall condition of plants and their productivity. Although the changes are not as impressive in comparison with other crops, for corn this may be an indicator of a possible increase in the efficiency of cultivation in the agroclimatic conditions of the Kharkiv region.

The greatest interest was aroused by the effect of electromagnetic radiation on soybeans. Soy is a relatively less common crop in the agro-industrial complex of the Kharkiv region, which is due to a number of agroclimatic factors, in particular, the limited thermal resource and insufficient amount of solar radiation necessary for its full growth and development. In the control group, the average plant height was only 52 cm, which is quite low for this crop. However, in the group that was exposed to electromagnetic radiation, the height of the plants increased to 62 cm, which is 19.23% more.

The mass of the root system also showed substantial changes: in the control group it was 8 g and in the experimental group – 10 g, which indicates a 25% increase. This result is especially important for soybeans, as root mass is a key indicator of plant development, which determines its resistance to stress and the efficiency of absorbing nutrients from the soil.

One of the important aspects of the study is the assessment of plant resistance to infections, fungal and bacterial diseases after exposure. Radiation exposure can alter the activity levels of antioxidant systems, which in turn help reduce exposure to diseases. In addition, it can affect the increased immune response of plants due to changes in their metabolism (Balan & Aheieva, 2018). Based on the results, it was established that in the experimental groups (with medium and strong levels of radiation exposure), a substantial decrease in the level of plant damage was observed compared to the control groups.

During each stage of exposure, the level of disease damage was reduced compared to the control groups. The greatest effect was observed in groups with medium and strong irradiation, which indicates the ability of electromagnetic radiation to strengthen the mechanisms of plant protection against diseases.

The calculation of the lesion index for three cultures was based on data on the degree of lesion in the control and experimental groups. For wheat (pyrenophorosis):

1. Control Group: A1 – 20, average lesion score b1 – 4 (substantial lesion).
2. Experimental group (medium exposure level): A2 – 20, average lesion score b2-2 (weak lesion).
3. Total number of plants N – 50:

$$\text{I control} = \frac{20 \cdot 4}{50 \cdot 5} \cdot 100\% = 32\%,$$

$$\text{I experiment} = \frac{20 \cdot 2}{50 \cdot 5} \cdot 100\% = 16\%.$$

For soybeans (multi-coloured mould):

1. Control group: A1 – 15, average lesion score b1 – 5 (severe lesion).
2. Experimental group (strong exposure level): A2 – 15, average lesion score b2 – 3 (moderate lesion).
3. Total number of plants N – 40:

$$\text{I control} = \frac{15 \cdot 5}{40 \cdot 5} \cdot 100\% = 37.5\%,$$

$$\text{I experiment} = \frac{15 \cdot 3}{40 \cdot 5} \cdot 100\% = 22.5\%.$$

For corn (corn rot):

1. Control group: A1 – 25, average lesion score b1 – 3 (moderate lesion).
2. Experimental group (average exposure level): A2 – 25, average lesion score b2 – 1 (weak lesion).
3. Total number of plants N – 50:

$$\text{I control} = \frac{25 \cdot 3}{50 \cdot 5} \cdot 100\% = 30\%,$$

$$\text{I experiment} = \frac{25 \cdot 1}{50 \cdot 5} \cdot 100\% = 10\%.$$

Thus, for all three crops, a substantial decrease in the lesion index was observed in the experimental groups compared to the control groups, which indicates a positive effect of electromagnetic radiation on plant resistance to diseases. These results correspond to the average radiation level (81-120 Hz) for the three types of crops. Generalised data on the effect of radiation exposure on the number of healthy plants can be seen in Figure 1.

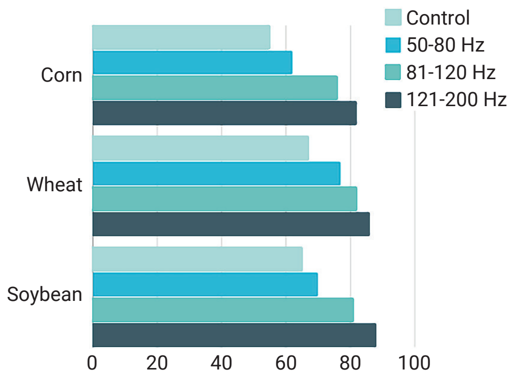

Figure 1. *Number of healthy plants (%) at different levels of pre-exposure to seeds*
Source: compiled by the authors

These results are important because they demonstrate substantial potential for using electromagnetic radiation to stimulate soybean growth and increase soybean yields in regions with limited growing conditions. In particular, changes in the development of the root system, plant height, and yield show that irradiation can contribute to improving the overall condition of soybeans and increasing their productivity, which is of great importance for expanding the production of this crop in Ukraine.

The difference in the reactions between wheat, corn, and soy to electromagnetic radiation in the experiment may be due to several factors that are both biological and agrotechnical in nature. For a better understanding, it is worth considering the genetic characteristics of each crop, the biological processes occurring in their cells under the influence of electromagnetic radiation, as well as the agrotechnical aspects of growing each crop in specific conditions of the Kharkiv region.

Wheat and corn have a more developed root system and mechanisms for adapting to stresses such as changes in environmental conditions. Wheat, as an annual grain crop, is adapted to a wide range of temperatures and lighting, which allows it to respond to electromagnetic radiation with minimal negative consequences at medium intensity. Accordingly, the average radiation level (150 Hz) contributed to an improvement in metabolic processes, such as photosynthesis, and provided optimal conditions for plant growth.

Corn, as a crop with a greater ability to actively absorb water and nutrients through the root system, also showed positive results under medium exposure. The strength of this plant species lies in its ability to quickly adapt to different climatic conditions, which allows it to use electromagnetic waves more efficiently to stimulate growth at a lower dose of radiation. However, at high radiation intensity (200 Hz), corn began to show negative effects, which may be the result of disruption of the normal functioning of the cell membrane caused by excessive radiation energy. This may be due to increased levels of oxidative stress and impaired plant metabolism (Kovalenko *et al.*, 2020).

Soy, unlike wheat and corn, showed the greatest changes in results due to its growth characteristics and biological sensitivity. Soybeans are more sensitive to environmental changes such as light levels and temperature, making them more vulnerable to environmental stresses, including electromagnetic radiation. The greatest stimulating effect was observed at a medium level of exposure, which was likely optimal for this culture. However, at high exposure intensity, soybeans showed slow growth, which may result from disruption of the normal development of the root system and a decrease in the ability to fix nitrogen in the soil, which is critical for soybean growth (Haidai, 2019; Osokina *et al.*, 2024).

Wheat and corn have a higher tolerance to electromagnetic radiation due to their adaptive mechanisms, such as more active regulation of water balance and greater ability to photosynthesise even under changing conditions. This allows them to use electromagnetic energy more efficiently to stimulate growth in the early stages of development. Thereby, soy, as a legume crop, has other biological needs, such as optimal root system growth for nitrogen fixation. High levels of radiation exposure can disrupt these processes, reducing the ability to develop and grow normally, as well as integrate nutrients.

Soy may also be more sensitive to energy changes at the cellular level due to its ability to symbiosis with nitrogen-fixing bacteria, which are critical for its normal development. High radiation intensity can disrupt normal biochemical reactions in plants, which can affect the effectiveness of nitrogen fixation and overall plant growth.

In addition to biological and genetic reasons, the agrotechnical conditions in which the experiment was conducted are important. For each crop, different growing conditions, such as soil temperature, humidity, and lighting, may have affected the effectiveness of exposure (Shaked *et al.*, 2001; Semenov *et al.*, 2017). In the case of corn and wheat, which are less sensitive to such changes, the results were less dependent on environmental conditions, compared to soybeans, which, due to their developmental characteristics, may be more vulnerable to changes in parameters such as light intensity and temperature.

Therefore, the difference in crop responses may be related to their genetic characteristics, physiological processes, and agrotechnical conditions. Wheat and corn showed improved growth and development at medium exposure levels due to their adaptation to changing environmental conditions and biological resistance to stress. Soy, on the other hand, showed better results at moderate levels of exposure, but at high intensity, there were substantial negative effects due to disruption of key biochemical processes. These data allow evaluating not only the effect of radiation on plant growth but also its ability to increase the stress resistance of plants, which is an important aspect for increasing yield and resistance to adverse conditions.

Discussion

The results confirmed that electromagnetic radiation has a positive effect on the growth and development of wheat, corn and, most importantly for the context of discussion, soybeans. Research shows that exposure to soybean seeds contributes to increased biomass and yield in conditions that are usually less favourable for this crop. During the study, it was established that wheat and corn also respond to radiation but their response was less substantial compared to soy. This may be due to the fact that these crops are already adapted to the conditions of the region, and electromagnetic stimulation does not play a crucial role in their productivity.

A similar effect of electromagnetic radiation on plant growth has been considered in other studies. For example, a study by L. Chervinsky & O. Romanenko (2016) analysed the spectral requirements for artificial irradiation for growing plants in closed-ground structures. Despite the similarity in the analysis of the effects of different radiation parameters, the current study has important differences. It covers the effect of electromagnetic radiation not only on certain growth parameters in artificial conditions but also in open field conditions of the Kharkiv region. This allows considering the importance of climatic factors and assessing the resistance of plants to natural stress factors.

A study by M. Marenych & S. Yurchenko (2017) was devoted to the examination of the effect of pre-sowing seed treatment with biologically active substances on the growth and development of winter wheat plants in the early stages. The similarity with the experiment lies in the general idea of influencing the initial stages of plant growth through seed treatment, which in the context of this study was conducted using electromagnetic radiation. However, the current study is more versatile, as it includes not only the impact on growth but also on other biometric indicators (for example, root system development and stress resistance, expanded by examining the reactions of different crops (wheat, corn, soybeans) and the impact on their productivity in real-world field conditions.

A paper of A. Semenov *et al*. (2017) is closely related to this study, as it focuses on the role of ultraviolet radiation in the development and productivity of various crops. Their study demonstrates how specific radiation ranges can substantially affect physiological processes in plants, in particular, metabolism, stress resistance, and increased yields. This publication is particularly important for understanding how the electromagnetic radiation used in the experiment can affect plant growth and development, which is also important for agricultural research.

H. Balan & O. Aheieva (2018) focused on the importance of predicting the development of diseases in agricultural production. They consider the impact of various adverse environmental factors on plants and their resistance to diseases, which is an important aspect of effective crop management and plant protection. The current study, in particular, examines exposure to electromagnetic radiation, which is an important additional variable in the context of stressors that can affect plant health. Although there are differences in approaches (electromagnetic radiation versus traditional agronomic factors) between the two reviews, both studies contribute to a deeper understanding of plant interactions with adverse environmental conditions and adaptation mechanisms. The current study may complement the recommendations of H. Balan & O. Aheieva (2018), in particular, in terms of how various stressors affect the development of diseases and the general condition of plants.

It is important to pay attention to international experience, which demonstrates substantial results in improving the sustainability and productivity of agricultural crops under the influence of various factors. S. Premaiatha *et al.* (2006) focus on the analysis of necrosis genes and assess wheat rust resistance, which is an important aspect of plant stress resistance. The current experiment also allows analysing the resistance of crops to various stressful conditions, such as diseases and adverse climatic factors. The general focus is on finding ways to increase the resilience of crops to external threats. However, the current study places more emphasis on technological aspects, in particular, on the use of the latest radiation methods to stimulate plant growth and development, which is a distinctive feature.

A study by J.M. Christie *et al.* (2012) focused on the role of the UVR8 photodetector in plants, which is activated by UV-B radiation due to the destruction of salt bridges between dimers caused by tryptophan. Researchers have investigated the molecular mechanisms by which plants are able to sense UV-B light and adapt their physiology to this factor. Similar to their study, the current paper also examines the effects of external physical factors but focuses on electromagnetic radiation and its ability to alter physiological processes such as growth, metabolic changes, and plant resistance in the field. The new study is unique in that it is aimed at exploring the agricultural impact in specific climatic conditions, which allows evaluating the results in an applied context for agricultural productivity and optimisation of growing conditions.

M. Wada *et al.* (2005) considered the mechanisms of plant photosensitivity, the interaction of plants with various types of light signals, such as phytochromes, cryptochromes, and other photoreceptors. They provided information on photomorphogenesis, including the effect of different light spectra on plant development, which is of great importance for understanding plant adaptation to changing environmental conditions. In the context of a new study that examines the effects of electromagnetic radiation, the concept of plant light sensitivity can serve as an important basis for comparison. Although this paper focuses on electromagnetic waves, the principles of plant adaptation to light stimuli may seem similar, highlighting the importance of external physical factors for plant growth and development.

Thus, the current study supports the hypothesis of a positive effect of electromagnetic radiation on crop productivity, especially in conditions that are unfavourable for soybean cultivation. This opens up new opportunities for further improvement of agricultural technologies and promotion of sustainable development of the agro-industrial complex in Ukraine and abroad.

Conclusions

The conducted study showed that electromagnetic radiation in the range of 50-200 Hz has a positive effect on the growth and productivity of agricultural crops, in particular, wheat, corn, and soybeans, in the agroclimatic conditions of the Kharkiv region. An increase in biometric indicators, such as plant height and root system mass, was noted. Especially substantial changes were recorded in soybeans, which usually show lower growth and development indicators in the Kharkiv region. Under the influence of electromagnetic radiation, there was an increase in soybean growth by 19.23%, root system mass – by 25% and a decrease in the crop morbidity index by 15-20%. This confirms the effectiveness of using electromagnetic radiation to increase plant resistance to diseases and improve their overall condition, which is promising for increasing productivity in the agricultural sector. The results obtained allow recommending the introduction of electromagnetic irradiation technologies within the specified range to improve crop productivity in regions with similar agroclimatic conditions. The greatest effect is observed when growing soybeans which traditionally have a low yield in the Kharkiv region. The use of this technology can also be useful in regions with insufficient natural light or unfavourable conditions for growing crops. It is advisable to analyse the optimal modes of electromagnetic exposure to further improve the results, in particular, the frequency and duration of exposure for each culture. It is also necessary to assess the impact on other crops and assess the long-term consequences for the agroecosystem, including the impact on soil microorganisms and soil fertility. One of the limitations of the study was its implementation in the same region (Kharkiv region), which may affect the universality of the results obtained. In addition, the limited duration of the experiment did not allow for assessing the long-term effect of electromagnetic radiation on soil yield and condition. In addition to optimising radiation modes, the effect of electromagnetic fields on the quality of final products should also be considered, in particular, on the protein and nutrient content in wheat, corn, and soy grains. This will help to understand whether electromagnetic radiation can improve not only quantitative but also qualitative indicators of the crop. It is also important to investigate the economic efficiency of implementing this technology in large agricultural enterprises, which will allow farmers to better assess the feasibility of using it in commercial agriculture.

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None.

Conflict of Interest

None.

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Вплив електромагнітного опромінення на ріст та продуктивність сільськогосподарських культур в агропромисловому комплексі

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Анотація. Метою цього дослідження було визначити особливості впливу різних рівнів електромагнітного випромінювання на біометричні показники та врожайність основних сільськогосподарських культур, таких як пшениця, кукурудза та соя. Дослідження було проведено на зразках пшениці, кукурудзи та сої, вирощених у агрокліматичних умовах Харківської області. Культури піддавалися впливу випромінювання в діапазоні від 50 до 200 Гц з використанням спеціального обладнання. Основні вимірювання включали аналіз біометричних характеристик: висоту рослин, кількість листя, масу кореневої системи, індекс захворюваності та загальну врожайність. Результати показали, що низькі рівні електромагнітного опромінення стимулювали ріст пшениці, підвищуючи врожайність на 12-15 %, а також збільшили кількість листя на 10-12 %. Для кукурудзи ефект опромінення виявився позитивним, зокрема спостерігалося збільшення маси кореневої системи на 18 % і зменшення індексу захворюваності на 15 %. Соя показала найбільший відгук на опромінення, з підвищенням росту на 19,23 %, маси кореневої системи на 25 % та зменшенням індексу захворюваності на 15-20 %. Висновки дослідження свідчать про потенційну можливість використання контрольованого електромагнітного випромінювання для підвищення продуктивності окремих сільськогосподарських культур, особливо сої у складних агрокліматичних умовах. Отримані дані можуть бути корисними для розробки нових технологій у сфері агропромислового комплексу, спрямованих на підвищення врожайності, сприяють досягненню цілей сталого розвитку, забезпечуючи більш екологічний підхід до підвищення врожайності та стійкості сільськогосподарських культур

Ключові слова: біометричні показники; врожайність; агротехнічні фактори; рослинна продуктивність