Preliminary Assessment of Electromagnetic Field Effects Induced by High and Medium Voltage Power Lines on Carbon Assimilation in Maize and Sunflower Crops

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Abstract
The purpose of the study is to analyze the impact of EMFs on the carbon footprint of agricultural crops, using sunflower (*Helianthus annuus*) and maize (*Zea mays*). The objective of the research is to develop an experimental model for evaluating the influence of electromagnetic fields generated by medium-voltage (1–35 kV) and high-voltage (35–275 kV) power lines on maize and sunflower crops. Considering that soil nutrient concentrations can vary significantly, assessing the impact of electromagnetic fields on crops, based solely on biomass accumulation, is challenging. Therefore, this study proposed the hypothesis that, under a constant atmospheric concentration of carbon dioxide, the total organic carbon content within plants should remain proportionally constant, regardless of the soil's nutritional conditions. The study was conducted in DB and Iasi (IS) counties for high-voltage lines, in Prahova (PH) county for medium-voltage lines and in Calarasi (CL) county as a control location without electromagnetic influences. The carbon content analysis in plants indicated that crops assimilate less carbon in areas exposed to high-voltage power lines in and sunflower and that medium-voltage lines positively influence carbon assimilation in sunflower. A deeper understanding of EMF-induced effects on the carbon cycle may provide a scientific foundation for adaptive strategies and optimization of agricultural practices, aiming to minimize environmental risks while maximizing soil capacity as an efficient carbon reservoir.

Keywords: high-voltage power lines, maize, sunflower, carbon dioxide, footprint

1. Introduction

In the context of global climate change and the need to reduce greenhouse gas emissions, agriculture plays a crucial role in managing carbon fluxes. The carbon footprint of agricultural crops is determined by the balance between CO_2 absorption through photosynthesis and emissions associated with biological and technological processes. Factors such as soil type, water regime, fertilization, microbial activity and agricultural practices directly influence carbon dynamics in agroecosystems [1].

An important aspect is the exposure of crops to electromagnetic fields (EMFs) generated by high-voltage power lines. Recent studies indicate that EMFs can affect plant physiological processes through non-thermal mechanisms, altering ionic signaling and cellular metabolism [2, 3]. Low-frequency electromagnetic fields (ELF-EMFs) can reach several µT (microtesla) near power lines [4], influencing photosynthesis and microbial activity in the soil. Additionally, EMFs impact Ca^{2+} (calcium ion) dynamics, affecting nutrient

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transport and carbon fixation processes in plant biomass.

Plants exposed to EMFs may exhibit significant changes in height, stem diameter, photosynthetic pigment content and transpiration rate [5, 6]. Some studies suggest that magnetic field exposure can stimulate germination, growth and plant stress tolerance, though the exact mechanisms remain unclear [7, 8]. EMFs can also influence soil microbial activity, affecting organic matter mineralization and CO_2 flux regulation.

In areas crossed by extra-high-voltage power lines, EMFs may interact with agricultural environments, altering photosynthetic rates, vegetative growth and nutrient accumulation. This can have implications for crop productivity and their ability to sequester carbon, requiring a detailed analysis of these effects.

This study aims to analyze the impact of EMFs on the carbon footprint of agricultural crops, using sunflower and maize as reference species due to their global agricultural importance. The research seeks to provide scientific data for optimizing the management of EMF-exposed crops and contribute to the development of sustainable strategies for agriculture near electrical infrastructure. Identifying EMF effects on the carbon cycle in agricultural ecosystems can support adaptive measures and the optimization of farming practices, minimizing risks and maximizing soil capacity as effective carbon reservoirs.

2. Materials and methods

2.1. Experimental design

The primary objective of this research was to determine the carbon footprint of major field crops (maize and sunflower) as a specific indicator for evaluating, classifying and quantifying commercial inputs based on the agricultural technologies applied in proximity to high-voltage power lines. The study aimed to develop an experimental model for analyzing the impact of electromagnetic fields generated by high-voltage power lines on these crops, investigating how exposure to such factors influences organic carbon accumulation and, consequently, the sustainability of agricultural systems near energy infrastructure.

The selected geographical study area was southeastern Romania, including the experimental plots located in DB county (high voltage), PH county (medium voltage) and Iași county (high voltage) (Figure 1). The results obtained were compared with those from a control area in CL county, which was not exposed to electromagnetic fields. The carbon footprint assessment was based on the estimation of sequestered carbon per hectare. The obtained carbon values in plant biomass were integrated into a model for estimating carbon sequestration per hectare. To determine the carbon sequestration capacity in plant biomass, total organic carbon analysis was performed on biological samples from roots, stems, leaves and fruits of the field crops in the studied areas, considering the implementation of the European Green Deal and the digitalization of agricultural processes [9].


(a) (b) (c)

Figure 1. High-voltage power lines passing through sunflower and maize crops: DB (a), PH (b), IS (c)

The data on fuel, pesticide, fertilizer, water and transportation consumption were organized into a database, converted into carbon equivalent and integrated into a spreadsheet-based carbon emissions calculation model. The determined carbon content values in plant organs were incorporated into a computational model and converted into the amount of sequestered carbon equivalent per hectare. Finally, the carbon balance was calculated as the difference between sequestered and emitted carbon.

To determine total organic carbon, 20 biological samples were collected from plants at different maturity stages, comprising 4 root samples, 4 stem samples, 4 leaf samples and 4 fruiting structure samples. For the calculation of CO_2 equivalence (kg/ha), total sequestered carbon and carbon balance (sequestered - emitted), the specific agricultural practices applied to each cultivated plant were considered (Table 1).

Table 1. Specific agrotechnical operations for each cultivated plant (original model)

Inputs	Agrotechnical operations	Maize (6000 kg/ha)	Sunflower (3000 kg/ha)
		Carbon [CO_2-eq kg/ha]	
Mechanization	Organic fertilizer application	27	27
	Chemical fertilization	9	9
	Plowing	86	86
	Harrowing	9	9
	Rotary tiller or cultivator use	30	30
	Sowing	13	13
	Rolling	6	6
	Herbicide application	3	3
	Mechanical weeding	28	28
	Phytosanitary treatment 1	19	19
	Phytosanitary treatment 2	19	19
	Mechanized harvesting	81	40
	Crop residue management	13	13
	Transport	97	48
Agrochemicals	Nitrogen	1085	542
	Phosphorus	38	19
	Potassium	39	19
	Fungicides	205	205
	Herbicides	530	530
	Insecticides	443	443
Other inputs	Irrigation, storage, etc.	0.89	0.89
Total		2808.95	2139.46

2.2. Sample analysis and research equipment

The sample analysis focused on the following parameters: vegetation water content (%), harvest water content (%), total carbon (%), harvested biomass yield (t/ha), biomass percentage (%) and the amount of sequestered CO_2 (t/ha). Biological samples were dehydrated using a thermobalance at 105°C until a constant mass was reached after three successive weightings. Total organic carbon content was determined using a TOC VCSN + SSM5000A analyzer for solids (Shimadzu Corporation, Japan), employing the combustion method at 900°C.

To evaluate the electromagnetic fields (EMFs) generated by medium-voltage (1–35 kV) and high-voltage (35–275 kV) power lines [10], an EMF510 (EXTECH INSTRUMENTS, USA) high-precision device was used to measure electromagnetic flux density (μT). Measurements were conducted at different distances from the power line (0-10-20-30 m) and heights from the ground (10 cm to 2.5 m), enabling the analysis of EMF distribution and its potential impact on agricultural crops.

2.3. Methodology for determining the carbon footprint in field crops

The research aimed to identify, classify and quantify commercial inputs used in agricultural crops, correlating them with the carbon sequestration capacity of crop biomass.

To determine the amount of sequestered carbon, measurements were conducted on biological samples collected from roots, stems, leaves and fruits at locations with the highest electromagnetic field intensity. The total organic carbon values obtained were integrated into a computational model and converted into the amount of carbon sequestered per hectare. The weighted average of percentages was used to estimate the total carbon content of the plant using the following formula:

$$Weighted\ percentage\ average = \frac{\sum(Pi * Wi)}{\sum Wi}$$

Where:
Pi = the percentage of organic carbon content
Wi = the percentage of each element weight
∑Wi = the total percentage of the plant (100).

Data related to fuel, pesticide, fertilizer, water and transportation consumption were organized into a database, converted into carbon equivalents and incorporated into a tabular carbon emissions model. The specific fuel consumption for performing agrotechnical operations was based on Annex 3 of Government Decision No. 109 of January 30, 2003, published in the Official Monitor No. 88 of 2003. To determine the carbon content of diesel fuel, a conversion factor of 0.732 was applied (CE kg/liter = diesel kg × 0.732). The conversion of carbon equivalent (CE) values into carbon dioxide equivalent (CO_2-eq) was performed using a factor of 3.67 (CO_2-eq = 3.67 × CE). The assessment of the carbon footprint of fertilizers was based on average values reported in the study by Walling, 2020 [11]. Carbon footprint values for the production of herbicides, fungicides and insecticides were referenced from the study by Helsel, 1992 [12]. Fertilization recommendations for the crops were aligned with specific input requirements, based on average yields of 3,000 kg/ha for sunflower and 6,000 kg/ha for maize.

Finally, the equivalent carbon balance was calculated by determining the difference between sequestered and emitted carbon, providing a quantitative assessment of the crops' impact on the carbon cycle.

3. Results and discussion

The total carbon levels in sunflower and maize crops were determined based on the following parameters: dried sample mass (mg), moisture percentage (%), drying duration (min) and ash content (mg) (Table 2).

The electromagnetic field (EMF) intensity near high-voltage power lines (Table 3) varies depending on the voltage level, current intensity, lateral distance and height from the ground. The highest recorded value was in DB county (5.9 µT) under the high-voltage line at a lateral distance of 10 meters and a height of 2.5 meters. In PH county, under medium-voltage lines, the maximum recorded value was 0.2 µT. In IS County, the highest EMF intensity was also observed at a lateral distance of 10 meters and a height of 2.5 meters.

3D interpolations of the electromagnetic field intensity indicate that in DB and IS counties, the field density increases vertically in proportion to height, while horizontally, it follows a parabolic curve, with peak values shifted laterally from the power lines. In contrast, interpolations of the EMF under the medium-voltage lines in PH show that field density increases proportionally with height but decreases as lateral distance increases, lacking the low-density buffer zone observed in high-voltage areas (Figure 2).

These findings suggest that crops located beneath high-voltage power lines are influenced by electromagnetic fields over a minimum width of 60 meters. Given that Romania had a total of 22,175 km of high-voltage power lines in 2018, the estimated affected agricultural area is approximately 133 km².

These observations are critical for agriculture near high-voltage infrastructure, as exposure to high-intensity EMFs can affect physiological processes such as photosynthesis and carbon accumulation. The non-uniform power density distribution indicates that the impact on crops is not constant and varies with distance and plant positioning relative to the radiation source. Further studies are necessary to assess long-term effects on agricultural ecosystems and to develop adaptive strategies for farming practices in areas exposed to high-intensity electromagnetic fields.

Table 2. Physicochemical parameters of sunflower samples based on distance from high-voltage power lines

Lateral distance	Parameters	Beneath high-voltage lines	10 m	20 m	30 m
DB county	Dry mass (mg)	32.1	38.2	37.3	30.8
	Moisture (%)	67.9	61.8	62.7	69.2
	Ash (mg)	1.5	1.3	1.3	1.0
PH county	Dry mass (mg)	32.0	35.1	30.5	32.6
	Moisture (%)	68.0	64.9	69.5	67.4
	Ash (mg)	0.15	0.05	0.01	0.12
IS county	Dry mass (mg)	39.9	29.4	37.6	41.8
	Moisture (%)	60.1	70.6	62.4	58.2
	Ash (mg)	2.2	0.7	1.8	0.3

Table 3. Electromagnetic field intensity (µT) at different heights and distances from high-voltage power lines

Height	DB county				PH county				IS county			
	Under line	10 m	20 m	30 m	Under line	10 m	20 m	30 m	Under line	10 m	20 m	30 m
10 cm	0.6	0.0	0.1	0.6	0.3	0.1	0.1	0.0	0.7	0.0	0.1	0.6
1 m	0.7	0.3	0.4	0.5	0.2	0.1	0.2	0.0	0.4	0.4	0.4	0.6
1.5 m	1.5	2.5	1.3	0.7	0.2	0.2	0.2	0.0	1.0	2.6	1.4	0.8
2 m	2.6	4.2	2.5	0.7	0.2	0.1	0.2	0.0	1.6	4.3	2.7	0.8
2.5 m	3.7	5.9	2.7	0.6	0.3	0.2	0.2	0.0	2.7	5.1	2.9	0.7

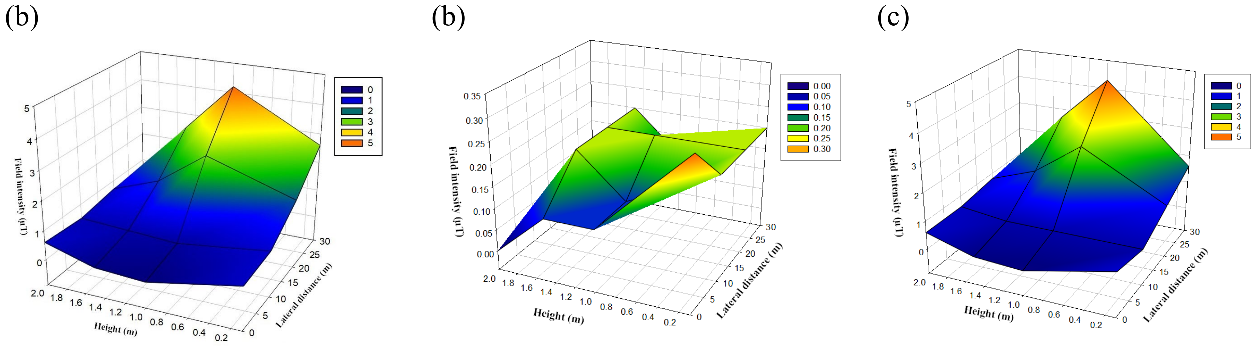

Figure 2. Electromagnetic field intensity in DB (a), PH (b) and IS (c).

The determination of total organic carbon content in maize and sunflower plant organs, performed through combustion analysis, highlights significant variations depending on location and exposure to electromagnetic fields (EMFs) from high-voltage power lines. When comparing exposed crops with control plots in CL, where no EMF influence is present, it was observed that maize cultivated in IS exhibited a significant reduction in root carbon content (18.58%) compared to the control sample in CL (47.48%). This suggests a potential negative impact of EMFs on carbon accumulation and nutrient absorption processes. Similarly, TOC values in stems and leaves were lower in IS, indicating that EMFs may influence photosynthetic efficiency and carbon transport within the plant.

Table 4. Total organic carbon content (%) in plant organs based on crop (a) (b) type and location

	Biomass percentage [%]	Harvested organ	DB county	PH county	CL county
SUNFLOWER	13	Root	41.30	47.35	47.02
	35	Stem	41.21	45.49	45.34
	15	Leaf	41.86	47.61	38.71
	37	Capitulum	42.13	46.65	48.37
	100	Total Carbon	41.66	46.48	45.69
MAIZE			IS county		CL county
	9	Root	18.58		47.48
	40	Stem	41.93		47.47
	10	Leaf	47.53		45.65
	41	Ear	42.10		46.67
	100	Total Carbon	40.46		46.96

Note: The table presents the total organic carbon (%) in maize and sunflower, distributed by plant organ and biomass percentage.

In contrast, sunflower showed less variability between exposed crops and control samples, with relatively stable TOC values. For instance, sunflower grown in PH, under EMF influence, displayed similar or even higher total carbon levels compared to the control lot in CL, suggesting a higher tolerance of this species to EMF exposure. These species-specific differences indicate that maize is more sensitive to electromagnetic disturbances than sunflower, potentially affecting its carbon sequestration capacity and overall yield.

Additionally, regional variations suggest that the impact of EMFs is not uniform and may be influenced by factors such as soil characteristics, climatic conditions and local electromagnetic field intensity. The results indicate that EMF exposure could reduce carbon accumulation in maize, potentially impacting productivity, whereas sunflower appears to be less affected. These findings are critical for the management of agricultural crops near high-voltage power lines, as they emphasize the necessity of continuous monitoring to evaluate EMF effects on plant metabolism and to identify appropriate adaptation strategies (Table 4, Figure 3).

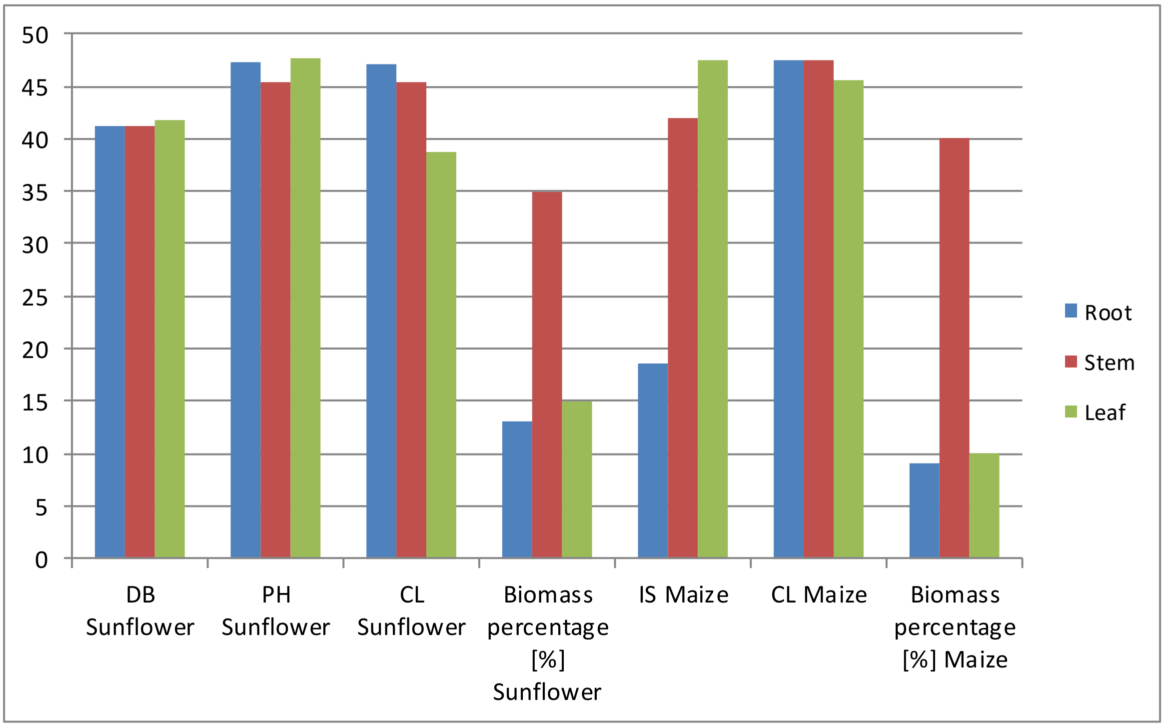

Figure 3. Distribution of total organic carbon content (%) in plant organs analyzed, based on crop type and location, CL no high-voltage exposure

The carbon content in sunflower crops exposed to different levels of electromagnetic fields was analyzed across three locations: DB (high voltage exposure), PH (medium voltage exposure) and CL (control). Descriptive statistics indicated that samples from DB exhibited lower carbon content compared to those from PH and CL. ANOVA analysis revealed a p-value of 0.052, suggesting that differences between the groups were close to statistical significance but did not meet the conventional threshold ($p < 0.05$). The non-parametric Kruskal-Wallis test further supported this, yielding a p-value of 0.092, indicating no statistically significant differences. These results imply a trend toward reduced carbon content under high voltage exposure; however, the effect was not strong enough to be deemed statistically significant based on the current dataset. The carbon content in maize crops was assessed in two locations: IS (high voltage exposure) and CL (control). Descriptive statistics suggested greater variability in carbon content among samples from IS. However, the ANOVA test yielded a p-value of 0.201 and the Kruskal-Wallis test a p-value of

0.248, both indicating no statistically significant differences between the two groups. These findings suggest that high voltage exposure did not produce a measurable effect on the carbon content of maize plants under the conditions of this study.

The experimental model for evaluating the carbon footprint was validated by comparing the estimated values with reference data from the scientific literature. The obtained values for total carbon emissions per kilogram of harvested crop were analyzed against international reference values [13, 14]. The results are presented in Table 5, while the comparison of reported emissions with international references is illustrated in Figure 4.

Table 5. Total carbon emissions per kilogram of harvested crop and per crop type compared to international reference values

Field crops	Total Carbon emission	International reference	Difference from reference
	($kg\ CO_2/kg$ harvested)		
IS (Maize)	0.581	0.4	+ 0.181
DB (Sunflower)	0.555	1.03	- 0.475
PH (Sunflower)	0.623	1.03	- 0.407

The analysis of total carbon emissions per kilogram of harvested crop reveals significant differences between crop types and locations compared to international reference values. Maize from IS recorded an emission of 0.581 kg CO_2/kg, exceeding the reference value by 0.181 kg CO_2/kg, indicating a potentially higher agricultural input consumption. Conversely, sunflower from DB and PH showed emissions of 0.555 kg CO_2/kg and 0.623 kg CO_2/kg, respectively, both below the international benchmark of 1.03 kg CO_2/kg, suggesting a more efficient carbon sequestration process. These findings highlight the importance of optimizing agricultural practices to reduce emissions and enhance crop sustainability

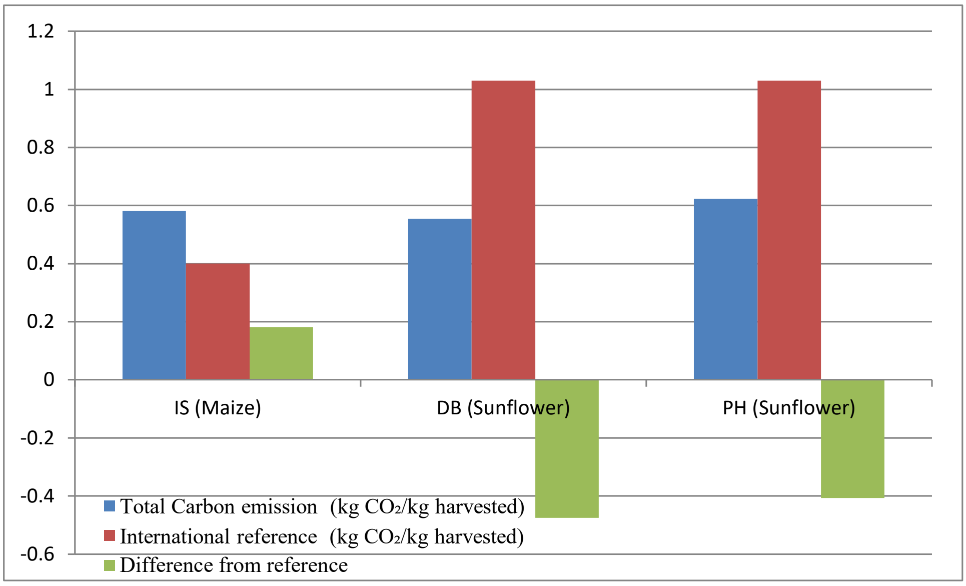

Figure 4. Comparison of total carbon emissions by crop type obtained in this study with international reference values

Electromagnetic fields (EMFs) generated by high-voltage power lines influence photosynthetic processes and carbon metabolism in plants, affecting their growth and development. EMF exposure can alter photosynthetic rates, chlorophyll content and enzymatic activity involved in CO_2 fixation, leading to variations in carbon absorption and utilization in physiological processes. Depending on the intensity and duration of exposure, plants may exhibit accelerated or inhibited growth, changes in height and stem diameter and color variations, ranging from deep green (indicating photosynthetic stimulation) to pale or yellowish tones (indicating oxidative stress).

EMFs also impact root development, reducing the plant's ability to absorb water and nutrients, while ionic imbalances can disrupt the transport of essential substances. The underlying mechanisms involve alterations in cellular electric potential, increased oxidative stress and disruption of natural bioelectric fields in plants. In the long term, these effects may affect agricultural productivity, necessitating further research to determine the precise impact and potential optimization or mitigation strategies for EMF exposure.

Finite Element Method (FEM) simulations and experimental analysis indicate variations in photosynthetic rates depending on EMF intensity and exposure duration. Previous studies [2, 3, 5] have reported similar effects, attributed to alterations in cellular bioelectric mechanisms. Research [6, 15] has demonstrated that EMFs influence ion transport and enzymatic activity involved in carbon fixation.

Experimental results from this study confirm that EMF exposure affects photosynthetic pigment content and CO_2 assimilation efficiency, effects associated with changes in stomata activity and the transport of water and nutrients, consistent with prior findings [16, 17]. Studies on the exposure of seeds and plants to low- and high-frequency EMFs [18, 19] suggest a positive effect on germination and plant growth. The results of this study indicate significant variability depending on plant species and exposure duration, highlighting the potential for optimizing EMF parameters to enhance agricultural yield [20]. Based on these findings, controlled EMF exposure could be used to stimulate physiological processes in plants; however, further biochemical investigations are necessary to determine long-term effects on agricultural productivity and crop quality.

Previous studies have analyzed the impact of EMFs generated by high-voltage power lines on human health and the environment, employing analytical methods and numerical simulations [21]. Research on magnetic field distribution near transmission lines has identified potential effects on ecosystems and human populations [22]. Investigations on 400 kV power lines, using image methods and Biot-Savart's law, demonstrated that measured field values at 1 m and 4 m above ground remain below the 100 µT limit set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [23]. Additional research on a 110 kV double-circuit power line in a residential area of Chernivtsi, Ukraine, evaluated magnetic flux density and proposed measures to reduce EMF levels below safety limits. These studies emphasize the importance of EMF monitoring and the implementation of mitigation measures to minimize their environmental and public health impact.

4. Conclusions

1. Maize cultivated under EMF shows a significant reduction in total organic carbon content, particularly in roots (18.58% in IS vs. 47.48% in the CL control plot), suggesting impaired nutrient absorption and root metabolism.
2. Sunflower exhibits greater EMF tolerance, with relatively stable total organic carbon levels compared to control plots, indicating a lesser impact on its metabolism.
3. EMFs influence photosynthesis and carbon metabolism, leading to variations in plant growth, chlorophyll content and enzymatic activity involved in CO_2 fixation, potentially affecting agricultural productivity.
4. EMF exposure may impact root development and nutrient uptake, contributing to metabolic imbalances and reduced soil resource efficiency.
5. Long-term monitoring of EMF effects on agricultural crops is essential, as responses vary depending on species, location and exposure intensity. Adaptive measures may be necessary to optimize yield in EMF-exposed crops.
6. High carbon emissions from maize in IS suggest increased resource consumption, whereas sunflower in DB and PH demonstrates more efficient carbon sequestration. These findings highlight the importance of optimizing agricultural technologies to reduce the carbon footprint and enhance sustainability.
7. The determination of carbon content in plants exposed to electromagnetic radiation stands

out as a relevant method for assessing its effects, given that the atmospheric concentration of carbon dioxide remains constant, while the variability in soil mineral concentration affects only the total amount of fixed carbon, not the carbon concentration within plant tissues.

8. The experimental model for evaluating the carbon footprint was validated by comparing the estimated values with reference data from the scientific literature.

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