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Integrating Extremely Low Frequency Magnetic Field Studies in Science Education: "A Case Study on 500 kV Extra High Voltage Transmission Lines"

Sudarti[1]*, Sumardi[2], Singgih Bektiarso[3], Wahyu Muldayani[2], Dina Helianti[4], Ayu Munawaroh Aziz M[4], Aditya Kurniawan[5], Rio Dermawan[3], Tania Ardiani[6], Rista Setiani[3]

[1] Doctoral Program in Science Education, University of Jember, Jember, Indonesia
[2] Faculty of Engineering, University of Jember, Jember, Indonesia
[3] Physics Education Department, University of Jember, Jember, Indonesia
[4] Faculty of Medicine, University of Jember, Jember, Indonesia
[5] Biology Education Department, University of Jember, Jember, Indonesia.
[6] Faculty of Medicine, University of Ailrangga, Surabaya, Indonesia

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Corresponding Author:
Sudarti
sudarti.fkip@unej.ac.id

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Abstract: Introduction: Until now, the impact of Extremely Low Frequency electromagnetic field radiation (ELF-EMF) by extra high voltage transmission lines (500 kV-EHVTL) is still debated. While WHO recommends a threshold of magnetic field exposure of 100 µT for up to 24 hours/day is declared safe for health. This study aims to examine the Integration of Extremely Low Frequency Magnetic Field Studies in Science Education: "Case Study on 500 kV-EHVTL". This study is important to support literacy in Environmental Physics and Environmental Radiation courses. The location of the study is a 500 kV EHVTL building located in Gondang Wetan District, Pasuruan Regency, East Java, Indonesia. Measurement of ELF magnetic field intensity using the EMF Tester-827 tool. The measurement position is at point 0 (directly below), and lateral distances of 50m, 100m, 150m, 200m, and 250m from the EHVTL power grid cable, as well as distances of 0m, 1m, 5m, 10m, and 15m from the EHVTL power grid tower. The intensity of ELF magnetic field exposure just below the EHVTL reached a value of 5.73 µT-10,085 µT (increased 170-234 times) compared to the natural magnetic field. While several research results prove that exposure to magnetic fields with an intensity of around 10 µT in vitro causes an increase in cell proliferation. Increased cell proliferation in the human body can have negative effects on health. Based on the research results it was concluded that an increase in the intensity of ELF magnetic field exposure up to 170-234 times can cause biological effects at the cellular level and has the potential to cause health impacts on humans. it is advisable to avoid living under the EHVTL network, and the WHO recommendation that the threshold exposure value of 100 µT is declared safe for humans exposed for up to 24 hours/day needs to be reviewed.

Keywords: 500 kV EHVTL; ELF Magnetic Field; Health Effect

Introduction

The development of electricity infrastructure in Indonesia, especially in East Java, continues to grow along with the increasing need for electrical energy. One important component in the distribution of electricity is the Extra High Voltage Transmission Line (EHVTL) which functions to transfer energy from the power plant to the consumption center over long distances. With a voltage of up to 500 kV, SUTET is designed to reduce energy loss during transmission, allowing for more efficient energy distribution. This is very important considering the vast territory of Indonesia which

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consists of many islands, where not all regions have power generation resources.

The electric power system consists of three main parts: generation, transmission, and distribution. The transmission system plays a role in carrying electrical energy from the power plant to the main substation with high or extra high voltage (HVS/EHVS) to other main substations. Transmission reliability is highly dependent on good management, especially because the EHVTL line passes through open areas that are vulnerable to interference, both from internal and external factors such as natural phenomena, animals, plants, and human activities (PLN(PERSERO), 2014). This transmission network plays an important role in supporting the availability of electrical energy for the community.

Naturally, humans are always exposed to electric and magnetic fields, given that the earth is a natural source of both fields. Along with the increasing use of electricity-based electronic devices in daily life, exposure to electromagnetic waves in the surrounding environment is also increasing (Situmorang et al., 2020). In recent years, concerns have been growing about the potential impacts of electromagnetic field exposure from EHVTL on public health. Individuals living or working near these transmission lines are often concerned about the health risks that may arise from long-term exposure to ELF-EMF fields (Saliev et al., 2019). This has led to a need to understand the extent of this exposure and whether there are safe limits to be considered.

Extremely low-frequency electromagnetic field (ELF-EMF) are a type of electromagnetic field generated by electrical power sources, including 500 kV EHVTL. This field has a frequency below 300 Hz and is naturally generated by electrical equipment and transmission systems (Moon, 2020). Although the intensity of this field is lower compared to high frequencies such as radio waves, long-term exposure to ELF-EMF fields raises concerns about their impact on human health.

ELF-EMF field exposure peaks at the center of the transmission line phase and decreases significantly as the lateral distance from the conductor increases (Houicher & Djekidel, 2021). Based on WHO guidelines, the level of magnetic field radiation around the 150 kV High Voltage Air Line (HVTL) is still below the safe threshold. Experts agree that electric and magnetic fields from transmission networks are classified as very low frequencies that have small energy, so they are unable to affect chemical bonds in human cells. In addition, the internal electric field in human cells is about 10 million volts/m, much stronger than the external electric field, and ELF fields do not cause heating effects like high-frequency electromagnetic waves.

Although some complaints such as headaches, dizziness, insomnia, and other disorders are reported by residents around the transmission network, these complaints are subjective and often influenced by perception (Deshayes-Pinçon et al., 2023). Research by Sudarti *et al*. (Sudarti et al., 2018) showed that the intensity of the ELF electric field around a 500 kV high-voltage electricity tower can increase up to 21 times compared to the control area, while the intensity of the magnetic field increases up to 9 times. However, this exposure remains below the threshold set by WHO.

Several studies have revealed a potential link between ELF field exposure and health problems. Biological and MRI test results indicate an increased risk of immune deficiency disorders, physical weakness, and behavioral problems in individuals living around high-voltage power (Aliyari et al., 2022). (Auger et al., 2019) found a correlation between the distance from the substation and an increased risk of cancer in children, although no direct causal relationship with the electricity transmission network was found. This study aims to examine the intensity profile of ELF magnetic field exposure by extra high voltage transmission lines (500 kV EHVTL), and its potential impacts on health. This research is important to support literacy in Environmental Physics courses.

Method

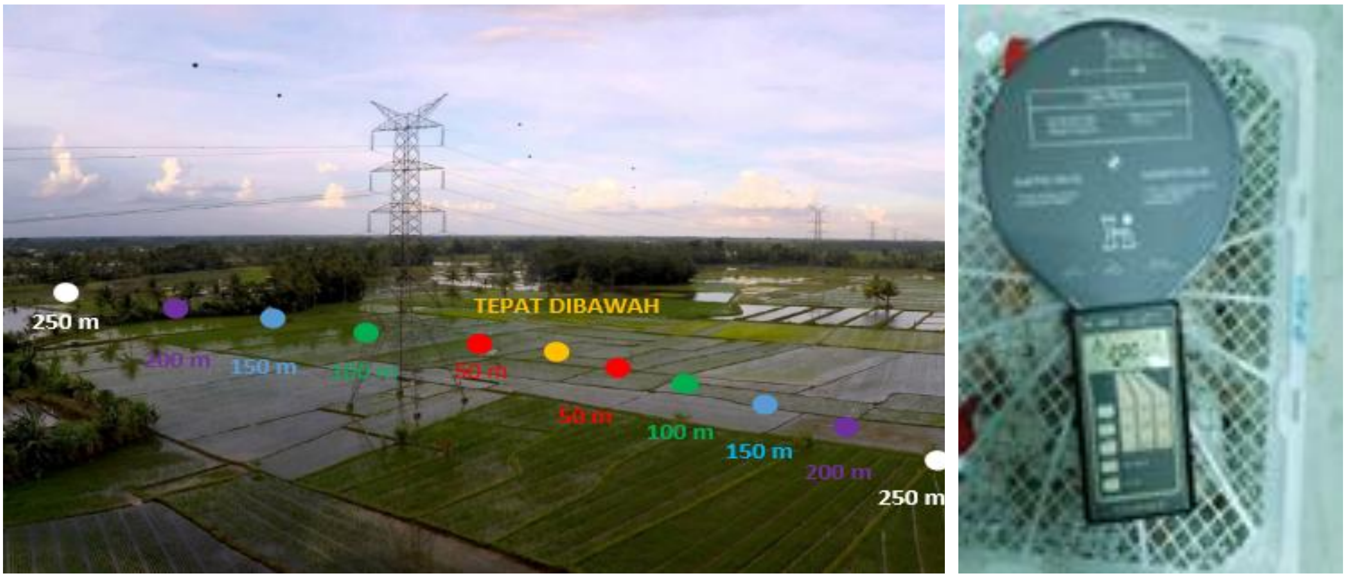
Location and Object of Research

This research is survey research with the research object being the 500 kV EHVTL building located in the Pasuruan area of East Java.The following presents the condition of the 500 kV EHVTL Network that passes over residential areas (See Figure 1).

Figure 1. 500 kV EHVTL Cable (Source: Personal Document)

ELF Magnetic Field Measurement Method by 500 kV EHVTL

Magnetic field measurements using the HI-3604 ELF Field Strength Measurement System, with specifications having a frequency range: 30 Hz - 300 Hz. Magnetic field measurements with a range: 0.1 mG - 20 G. Measurements are carried out at lateral distances to the left and right of the EHVTL 500 kV network axis projection, starting from a distance of 0 m (right on the network axis projection line), a distance of 50 m, 100 m, 150 m, 200 m, 250 m. The vertical position at a distance of 150 m from the ground surface, refers to the average height of an Indonesian human head, as seen in Figure 2.



(a) (b)

Figure 2. (a) Illustration of measurement points at 500 kV EHVTL, (b) HI-3604 ELF Field Strength Measurement System (Source: personal documents)

Image caption:
- = Right under the EHVTL
- = 50 m to the right and left of the EHVTL
- = 100 m to the right and left of the EHVTL
- = 150 m to the right and left of the EHVTL
- = 200 m to the right and left of the EHVTL
- = 250 m to the right and left of the EHVTL

The research data were analyzed with a descriptive approach as well as through comparative statistical analysisd.

Result and Discussion

The results of this study will discuss: 1) The distribution pattern of Extremely Low Frequency (ELF) magnetic field intensity under the network and around the 500 kV EHVTL Tower, and 2) Community protection efforts against the presence of 500 kV - EHVTL.

Natural magnetic field patterns

To evaluate the increased exposure to ELF magnetic field intensity at the 500 kV EHVTL, data on natural magnetic field intensity is required as a reference. The results of natural magnetic field intensity measurements at field locations far from the 500 kV EHVTL network or away from other electronic equipment, are presented in Figure 3.

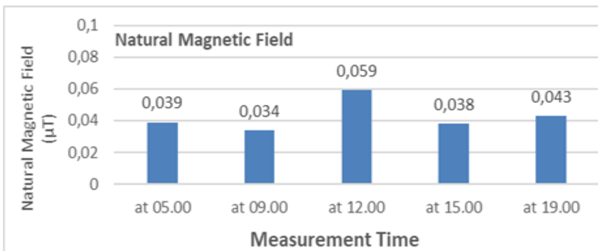


Figure 3. Intensity pattern of the natural magnetic field

Figure 3 shows the intensity pattern of natural magnetic field exposure. The highest intensity was recorded at around 12:00, which was caused by electromagnetic wave radiation from the Sun falling to the earth in a perpendicular position, so that the intensity of the electric field and magnetic field on the earth's surface became optimal.

Pattern of distribution of ELF magnetic field intensity under 500 kV EHVTL

The results of ELF magnetic field measurements around 500 kV-EHVTL are presented in Figures 3.

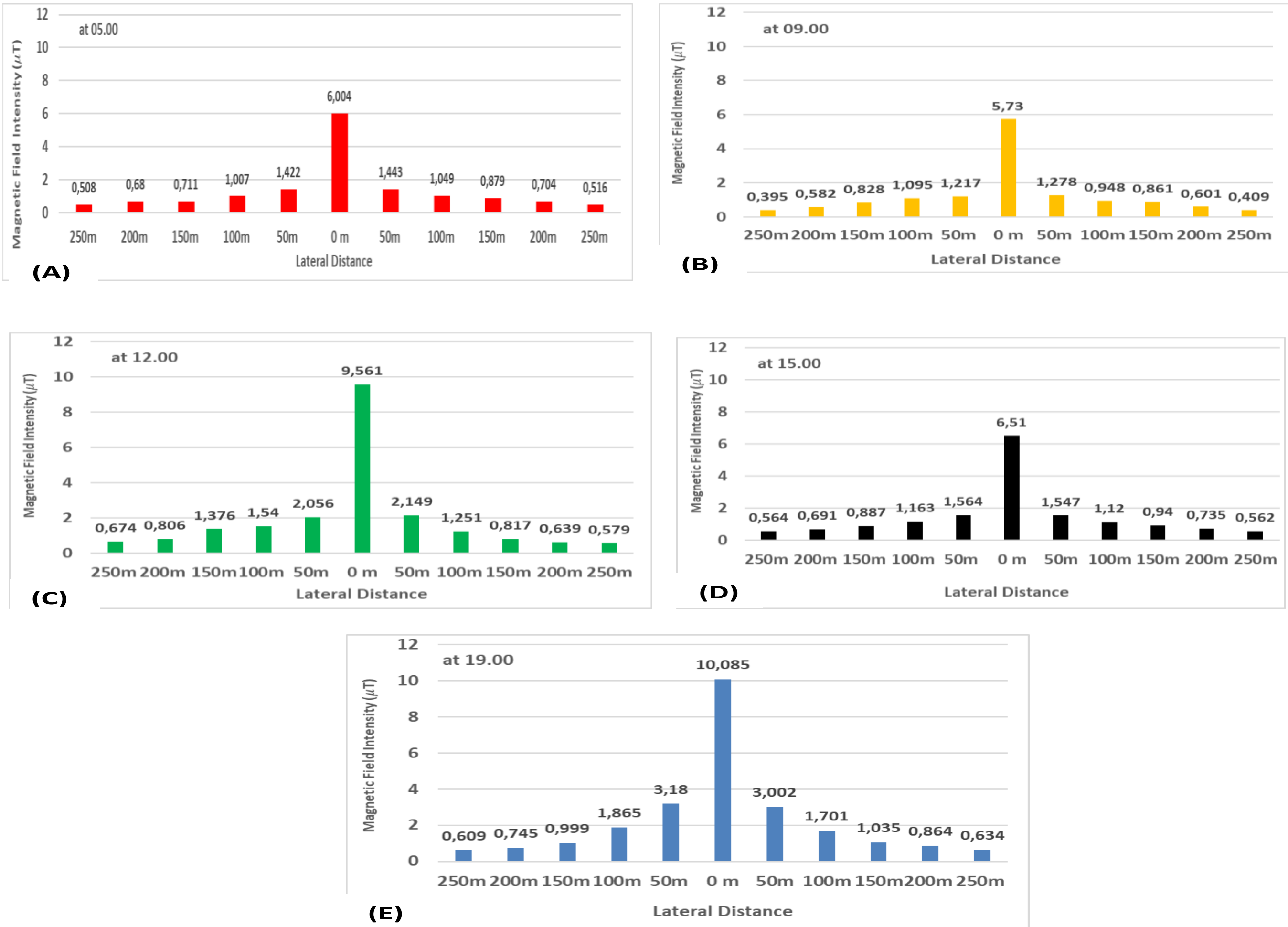


Figure 3. Pattern of ELF Magnetic Field Intensity below 500 kV - EHVTL Based on Measurement Results at: (A) 05.00, (B) 09.00, (C) 12.00, (D) 15.00, (E) 19.00

Figure 3 depicts the results of ELF magnetic field intensity measurements around the 500 kV EHVTL at 05.00 (A), at 09.00 (B), at 12.00 (C), at 15.00 (D), and at 19.00 (E). It is proven that throughout the time, the highest ELF magnetic field intensity is right under the network (at point 0 m) of the 500 kV EHVTL, with an intensity range of 5.73 µT to 10,085 µT or an increase of 170 times to 234 times compared to the natural field. The intensity of the ELF magnetic field at a lateral distance of 50 m is in the range of 1.9305 µT to 3.1565 µT, or an increase of 32 to 73 times from the natural magnetic field. Meanwhile, the intensity of the ELF magnetic field at a lateral distance of 250 m reaches 0.5120 µT to 0.8115 µT, or increases by about 11 times to 19 times from the natural magnetic field.

Furthermore, Figure 4 illustrates a comparison graph of the magnetic field intensity measured at 05:00, 09:00, 12:00, 15:00, and 19:00, with lateral distances to the left and right consisting of 0 m, 50 m, 100 m, 150 m, 200 m, and 250 m.

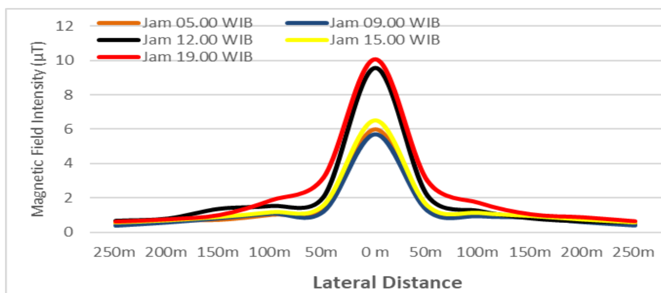


Figure 4. Measurement Data of ELF Magnetic Field Intensity at Lateral Distances

The measurement results showed that the highest value was recorded at 19:00, with a maximum intensity at point 0 m of 10.085 µT, while the lowest value occurred at 09:00 with a maximum intensity at point 0 m of 5.78 µT. One Way Anovaanalysis indicated that the ELF magnetic field intensity decreased significantly ($p < 0.05$) as the distance from the 500 kV EHVTL grid increased.

This proves that the area at a lateral distance of up to 250 m to the 500 kV EHVTL network is still exposed to a high ELF magnetic field, which is (3.1565 - 0.8115) µT or an increase of 73 - 19 times compared to the natural magnetic field.

Pattern of ELF Magnetic Field Intensity Around the 500 kV EHVTL Tower

The results of ELF magnetic field measurements around the 500 kV EHVTL Tower at a height of 1.50 m above ground level, with lateral distances to the left and right of 5 m, 10 m, and 15 m, at 05:00, 09:00, 12:00, 15:00, and 19:00, are presented in Figure 5.

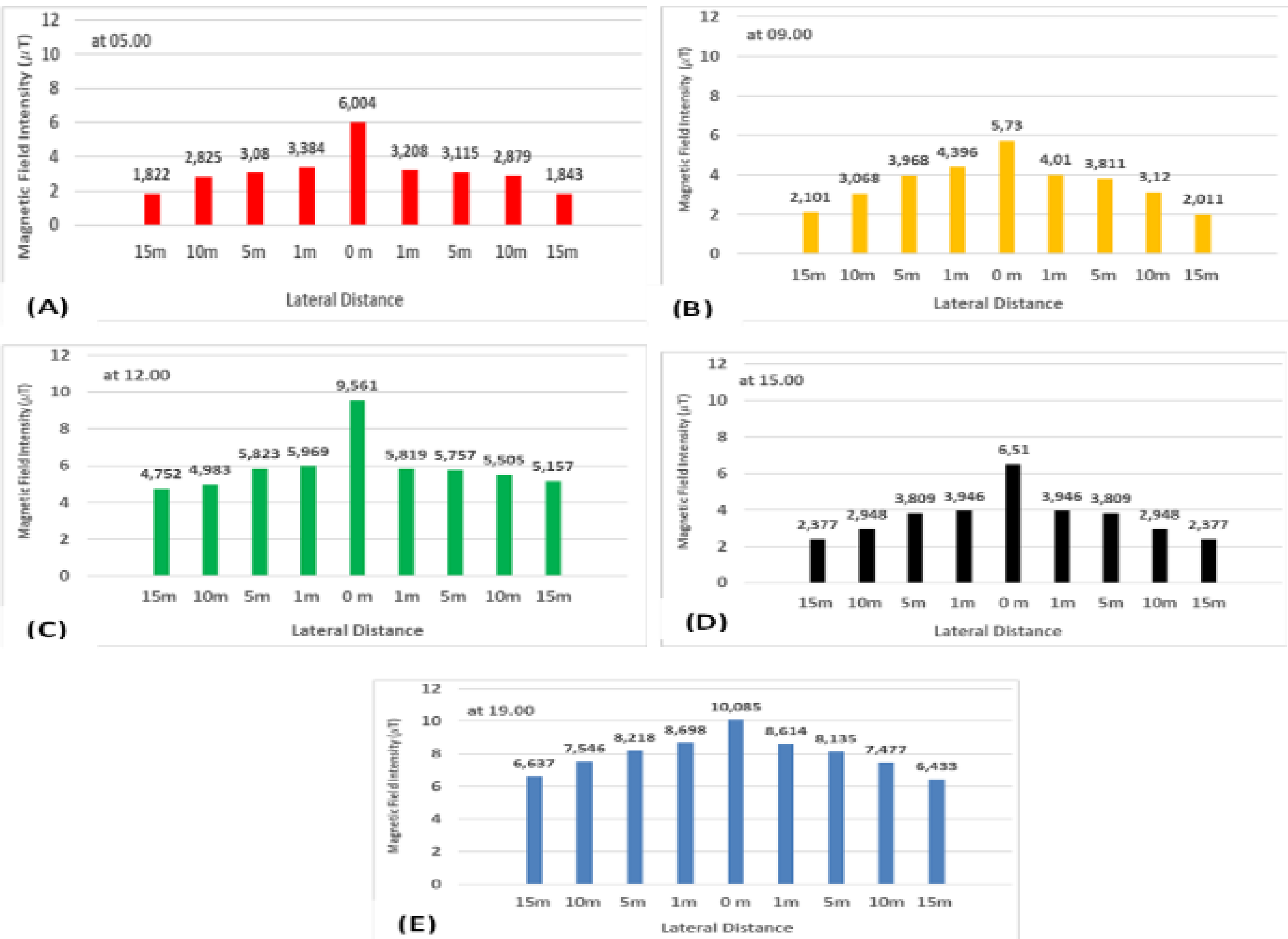


Figure 5. Pattern of ELF Magnetic Field Intensity Around the 500 kV EHVTL Tower Based on Measurement Results at: (A) 05.00, (B) 09.00, (C) 12.00, (D) 15.00, (E) 19.00

Figure 6 shows the results of ELF magnetic field intensity measurements around the 500 kV EHVTL Tower at 05.00 (A), 09.00 (B), 12.00 (C), 15.00 (D), and 19.00 (E). It is proven that the average ELF magnetic field intensity at a lateral distance from the tower foot of 0 m throughout the time is in the range of 5.73 µT to 10.085 µT or an increase of 170 to 234 times. The magnetic field intensity at a distance of 1m is around 3.0290 µT to 8.656 µT or an increase of around 77 times to 201 times, and at a distance of 15 m is around 2.377 µT to 6.535 µT or an increase of around 62 to 151 times compared to the natural field.

The sources of electromagnetic waves can be divided into two main categories: natural and man-made sources. For example, naturally generated electromagnetic waves can be grouped in the wave spectrum, which includes gamma rays, X-rays, ultraviolet rays, visible light, infrared, radio waves, and microwaves (Nur et al., 2022). The source of electromagnetic fields generated by humans and the focus of discussion is the 500 kV Extra High Voltage Air Line (EHVTL). The 500 kV Extra High Voltage Line (EHVTL) can emit electromagnetic waves, but the waves are classified as Extremely Low Frequency (ELF) electromagnetic waves because the frequency of the wave spectrum is below 300 Hz. These waves are also included in non-ionizing radiation, which is radiation that cannot cause ionization. Non-ionizing radiation itself is radiation with enough energy to remove electrons or molecules, but the energy is not enough to form or create new ion formations. According to the International Radiation Protection Association (IRPA) and the World Health Organization (WHO), the limit of magnetic field radiation allowed to not affect organisms and biology is 0.5 mT (milli tesla). Radiation is the release of energy through matter or space in the form of heat, particles, or electromagnetic waves/light coming from a radiation source.

This study aims to identify the increase in Extremely Low Frequency (ELF) magnetic field intensity around the 500 kV Extra High Voltage Line (EHVTL) compared to natural magnetic field intensity. In addition, this study also aims to analyze changes in ELF magnetic field intensity around the 500 kV EHVTL based on different distances and times. The results of measurements taken in the control area away from the artificial magnetic field source show an increase in the Extremely Low Frequency (ELF) magnetic field magnitude compared to measurements taken in the vicinity of the 500 kV Extra High Voltage Line (EHVTL), with measurements taken repeatedly at different times. According to the World Health Organization (WHO) and the International Radiation Protection Association (IRPA) that the safe threshold limit of magnetic field exposure that is allowed to exist does not affect organisms or biological effects for the public is 0.5 mT (milli tesla). In Figure 3, the distribution pattern of the natural magnetic field at the University of Jember field shows that at 05.00 WIB, the average magnetic field magnitude was recorded at 0.039 µT; at 09.00 WIB the average was 0.034 µT; at 12.00 WIB the average reached 0.059 µT; at 15.00 WIB the average was 0.038 µT; and at 19.00 WIB the average reached 0.045 µT. These measurements were taken in the center of the field and repeated 10 times.

Based on the data above, the graph shows that the measured magnetic field reaches its highest value at point 0 m, just below the 500 kV EHVTL. As the distance from the 500 kV EHVTL increases, the magnetic field magnitude decreases, because the magnetic field weakens as the distance from the source increases (Fikry et al., 2021). As in the right and left lateral distances, ranging from 50 m; 100 m; 150 m; 200 m; to 250 m, the magnetic field cannot be blocked by any material. Its intensity will still not decrease even if it passes through objects that are usually difficult to penetrate, such as human bodies, buildings, soil, or surrounding trees (Cahyono et al., 2023). Figure 4 shows the average ELF magnetic field magnitude at the wire crater, right lateral, and left lateral. At the position just below the 500 kV Extra High Voltage Line (EHVTL) at various predetermined times, the graph shows that the average ELF magnetic field magnitude in the morning at 09.00 WIB at point 0 meters (just below the EHVTL-500 kV EHVTL) reaches the lowest value, which is 5.73 µT. In comparison, the magnetic field intensity at 05.00 WIB was recorded at 6.004 µT, at 12.00 WIB it was 7.977 µT, at 15.00 WIB it remained at 7.977 µT, and at 19.00 WIB it increased to 11.503 µT. At 19:00 WIB, the magnetic field value reached its highest point with a significant increase in the ELF magnetic field magnitude at the 500 kV Extra High Voltage Line (EHVTL) of 10.085 µT. This increase is due to the increased use of electric power at night, which results in the magnetic field magnitude at that time being the highest. Based on the graph of the average magnetic field magnitude at 05.00 WIB, 09.00 WIB, 12.00 WIB, 15.00 WIB, and 19.00 WIB, it can be seen that in lateral positions to the right and left with distances of 50 m, 100 m, 150 m, 200 m, and 250 m, there is a consistent decrease in magnetic field magnitude when compared to the position just below the wire. The decrease in magnetic field intensity is caused by the distance between the measurement point and the magnetic field source, namely the 500 kV Extra High Voltage Line (EHVTL), as well as variations in measurement time which cause differences in the detected magnetic field values. When comparing the lateral distance magnetic field of the 500 kV Extra High Voltage Line (EHVTL) with the natural magnetic field, there is a significant difference.

At the measurement points on the west, east, north, and south sides of the tower, the average magnetic field intensity around the 500 kV EHVTL tower can be seen starting from a distance of 1 m, 5 m, 10 m, to 15 m, with the measurement times carried out at 05.00 WIB, 09.00 WIB, 12.00 WIB, 15.00 WIB, and 19.00 WIB. Figure 6 shows the magnetic field distribution pattern around the 500 kV Extra High Voltage Line (EHVTL) tower. At the north and south positions of the tower, the further away from the tower, the smaller the average value of the magnetic field. However, on the west and east sides of the tower, there is no significant difference in the average value of the magnetic field, because in the western and eastern positions of the tower, the location of the researcher is right under the conductor wire but there will be a significant difference when the measurement of the west and east of the tower is located in a position right in the middle between the 2 towers because in this position the conductor wire experiences expansion which causes the wire to extend downward so that the distance between the measuring instrument and the conductor wire is getting closer and produces a high value. This condition will vary with time and weather. In the picture, at 09.00 WIB, the magnetic field value reaches its lowest point, while at 19.00 WIB, the highest value is recorded. The increase in the average magnetic field value at 19.00 WIB is caused by the increased use of electricity at night, resulting in the maximum value of the 500 kV Extra High Voltage Air Line (EHVTL).

However, many factors affect the magnitude of the magnetic field generated including the EHVTL-500 kV, this comes from the influence of the external environment, for example, influenced by the magnetic field generated by electrical equipment that is lit around the research site and motorized vehicles passing through the research site, as well as the use of measuring instruments that can affect the accuracy of measurements, and others. The average measured magnetic field shows a distinct increase at any given time. In principle, the system voltage does not directly affect the magnetic field strength, because the magnetic field is more influenced by the magnitude of the electric current flowing through the channel. However, as the line voltage increases, the current carrying capacity also increases, which will ultimately strengthen the magnetic field around the line (Jedrzejczak-Silicka et al., 2021). The measured magnetic field strength fluctuates over time. Changes in the Earth's magnetic field are also affected by the rotation of the planet. The Earth's magnetic field is formed because of the Earth's magnetic characteristics, which originate from permanent magnetization produced by the flow of electric currents moving in and out of the Earth. In addition, the Earth's magnetic field is also affected by the solar wind and variations in solar activity (Mayrovitz, 2023).

According to research by Alwiyah *et al*. (Alwiyah et al., 2024) the intensity of the magnetic field in the morning is lower than at night, so the intensity of the magnetic field tends to increase as time goes by until the evening. The low magnetic field intensity in the morning is due to low load, meaning that the current flowing on the conductor wire of the electricity network is lower when compared to daytime or nighttime, so that the resulting magnetic field is low as well. During the day there is an increase in current on the conductor wire of the electricity network compared to the morning, so that the magnetic field value during the day is measured greater than the magnetic field value in the morning. At several measurement locations, significant variations in magnetic field strength were found at certain hours. In addition to being caused by increased electric current in the cable, other factors that affect the magnitude of the magnetic field are disturbances from the sun, such as the intensity of sunlight. During the day the sun emits more radiation to the earth than at night, the radiation emitted by the sun, one of which is included in ultraviolet radiation. Solar ultraviolet radiation causes ionization of the ionospheric layer (Bekker et al., 2021). This ionization, along with charged particles radiated from the sun, will cause current fluctuations that act as a source of magnetic fields. Ions formed from atmospheric layers ionized by sunlight turn into charged particles, and when there is an electric current in the ionosphere, the ions will function like a magnet.

Based on the results of research and measurements around the 500 kV Extra High Voltage Air Line (EHVTL) in Rembang Village, Rembang Regency, it was concluded that there was a significant increase in the intensity of the natural magnetic field and the Extremely Low Frequency (ELF) magnetic field in the area around the 500 kV EHVTL. From the graph, the highest magnetic field intensity was measured at the measurement point right below the 500 kV EHVTL at 19:00 WIB. However, the magnetic field value decreased as the distance from the 500 kV EHVTL increased. Even so, the ELF magnetic field produced by the 500 kV EHVTL is still below the limit recommended by WHO and IRPA, namely with an irradiation of 0.5 milli Tesla (mT).

Direct ELF Magnetic Field Interaction with Cell Membranes

Electromagnetic field exposure consists of electric and magnetic field components, each of which has unique characteristics. Electric fields tend to have a lower penetration ability than magnetic fields in the bodies of living things (Yulandari et al., 2024). This is because electric fields can be inhibited by tissue resistance, so that electric fields do not penetrate deep into the body and their effects are more pronounced in near-surface tissues, such as skin and subcutaneous tissue. Magnetic fields are not affected by tissue resistance, so they can penetrate the entire body and directly interact with cell membranes and ions in the body [23]. (Rotundo et al., 2022).

The ELF magnetic field directly interacts with the ions in the cell membrane through a magnetic force known as the Lorentz force. This force acts on ions that are in a dynamic state due to the cell's metabolic processes, thus allowing the modification of the membrane signal transduction process (Jedrzejczak-Silicka et al., 2021). In the context of blood circulation, the Lorentz force can affect ions such as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and chloride (Cl^-), which play a role in various physiological processes, including nerve signal transmission and maintaining electrolyte balance (Bau, 2022; Guo et al., 2022).

Exposure to an ELF electromagnetic field with a magnetic field intensity (B) will produce a Lorentz force (F) on an ion with charge q moving at a speed v, which can be formulated by the following equation (Panagopoulos et al., 2021):

$$\mathbf{F} = \mathbf{q} * (\mathbf{v} \times \mathbf{B}) \quad (1)$$

F is the cross product of the velocity vector and the magnetic field, which produces a force component perpendicular to the direction of the velocity and magnetic field. This suggests that the ELF magnetic field component can affect the direction of ion movement in cells, including blood cells and bone marrow cells.

Several studies have revealed that calcium ions (Ca^{2+}) have an important role in the interaction with ELF-EMF exposure (Díaz-Piña et al., 2024). Barati *et al*. (Barati et al., 2021) concluded that increased intracellular Ca^{2+} levels contributed to increased tumor cell apoptosis due to intermittent ELF-EMF (100 mT, 1 Hz) exposure for 2 hours daily for 28 days. Xia *et al*. (Xia et al., 2021) showed that the effects of ELF-EMF on synaptic plasticity are mediated through the Ca^{2+}/calcineurin pathway, where long-term ELF-EMF exposure can reduce synaptic plasticity and increase the risk of depression. Chen *et al*. (Chen et al., 2023) reported that intermittent exposure strategy is a promising method to optimize the therapeutic effects of 16 Hz ELF-EMF in bone fracture healing or osteoporosis, which is mediated by increased Ca^{2+} influx.

It is known that calcium ions play an important role in the process of cell proliferation, which includes cell division and growth (Cooper & Dimri, 2023). Changes in calcium concentration inside the cell will affect various signaling pathways that are important in the process of cell proliferation. (Vasileva et al., 2023). Calcium functions in activating various protein kinases that play an important role in cell proliferation, including mitogen-activated protein kinase (MAPK), which is involved in regulating gene transcription required for the cell cycle and cell growth (Tokumitsu & Sakagami, 2022). The balance between proliferation and cell death (apoptosis) is also affected by intracellular calcium levels. Calcium levels that are too high or too low can trigger apoptotic mechanisms, while well-controlled calcium levels favor cell proliferation. (Terrell et al., 2023).

The application of this concept is seen in the research of Sudarti *et al*. (Sudarti et al., 2024), who reported that exposure to ELF-EMF at low intensity (< 500 µT) increased the proliferation of Salmonella and E. Coli bacteria, while at high intensity (> 1000 µT), this exposure actually inhibited the proliferation of these bacteria, thereby extending the shelf life of chicken meat. In addition, exposure to ELF-EMF (15 mT; 120 Hz) for 5, 10, and 15 minutes for seven days was shown to increase cell apoptosis (Oladnabi et al., 2021).

Threshold Value of Exposure to ELF Magnetic Field by WHO

ELF electromagnetic fields produce very low energy, so their effects are not thermal in nature. This means that they do not affect the temperature of an object or cause a temperature change when interacting with matter. ELF magnetic fields have frequencies below 300 Hz and are a type of non-ionizing radiation. This means that the radiation energy produced is not strong enough to cause ionization in molecules. (Kamila & Sudarti, 2022). The exposure limits for electric and magnetic fields recommended by the World Health Organization (WHO) in 2007 can be seen in Table 1.

Table 1. Exposure Thresholds

Exposure To	Frequency Electric Field and Magnetic Field	Intensity (kV/m)	
		Electric Field	Magnetic Field
Worker Group	50 Hz	10 kV/m	500 µT
	60 Hz	8.3 kV/m	420 µT
General Group	50 Hz	5 kV/m	100 µT
	60 Hz	4.2 kV/m	83 µT

According to the established exposure limits, ELF magnetic fields in the environment are generally well below the threshold recommended by WHO (<100 µT). However, several studies have shown the potential risk of mild health problems due to exposure to low-intensity magnetic fields (<100 µT), so concerns about their impact on health remain. Therefore, the biological mechanism of ELF magnetic field exposure at intensities below 100 µT requires further research to understand it better.

Potential Health Effects by ELF Magnetic Field Exposure in the Vicinity of 500 kV EHVTL

The 500 kV Extra High Voltage Line (EHVTL) generates Very Low Frequency (ELF) magnetic fields that have the potential to affect human health. ELF magnetic fields, which are at very low frequencies (around 50-60 Hz), are often found in environments close to high-voltage electrical infrastructure such as EHVTL. Exposure of animals or biological samples to man-made electromagnetic fields (EMFs), especially at very low frequencies (ELFs) as well as microwave or radio frequencies (RFs) that often accompany ELFs, has the potential to damage DNA. This damage can lead to cell death, infertility, and various other health problems including cancer. (Panagopoulos et al., 2021).

Several studies have evaluated the potential health impacts that can occur due to exposure to ELF magnetic fields from EHVTL. One impact that is often of concern is the increased risk of cancer, especially leukemia in children. Some experts argue that exposure to ELF magnetic fields can increase the risk of leukemia in children (Malagoli et al., 2023). The results of the study showed that children who live less than 100 meters from power lines have a two-fold higher risk of developing leukemia compared to those who live more than 400 meters away.

In addition, several studies have also indicated that exposure to electromagnetic fields (EMF) can affect other physiological functions of the body. In a study involving Rhesus monkeys, exposure to electromagnetic fields with a frequency of 50 Hz and an intensity of 3 kV/m for 4 hours a day for 30 days caused an increase in the number of white blood cells, a decrease in the number of red blood cells, and an increase in adrenaline and glucose levels in the blood. Changes in the prefrontal area of the brain were also detected through MRI, and exposed macaques showed symptoms of behavioral disturbances such as fatigue, anorexia, and insomnia. These findings are a reminder that exposure to electromagnetic fields from high-voltage power towers can have negative impacts on health, particularly the immune system (Aliyari et al., 2022).

Another study involving 14 men working in an extra high voltage substation also revealed the impact of exposure to ELF magnetic fields on the secretion of cortisol, the main stress hormone in the body (Touitou et al., 2022). Workers exposed to ELF magnetic fields for a long period, with intensities ranging from 0.1 to 2.6 μT, showed significant changes in cortisol secretion compared to a control group exposed to magnetic fields at an intensity ten times lower. Blood measurements taken at regular intervals from night to morning showed that workers exposed to ELF-EMF had impaired peak cortisol secretion. This suggests that exposure to ELF magnetic fields may disrupt the balance of hormonal rhythms in the body, which may increase physiological stress loads and increase health risks, especially in more vulnerable groups such as children, the elderly, and patients with chronic health conditions.

The International Agency for Research on Cancer (IARC) classifies EMF as "possibly carcinogenic" to humans (Meena et al., 2016). A study by Cios *et al*. (Cios et al., 2021) examined the effects of low-frequency EMF on changes in clear cell renal carcinoma using four different cell lines, namely HEK293, 786-O, 769-P, and Caki1. The results showed that EMF had varying effects depending on the cell type. In renal cancer cell line 786-O, low-frequency EMF caused an increase in apoptosis, cell cycle arrest at G1 phase, and a reduction in the number of viable cells. However, in HEK293 cell lines, EMF did not affect cell proliferation or survival. Interestingly, EMF also showed inhibitory effects on the migration and metastatic ability of renal cancer cells, as well as increasing reactive oxygen species (ROS) levels after exposure. This study reveals that the impact of ELF magnetic fields can differ depending on the cell type and metabolic state of the exposed cells. These findings further strengthen the notion that electromagnetic fields, although not yet fully proven to be harmful to humans, have the potential to affect the body's cells, particularly cancer cells.

The intensity of ELF magnetic field exposure around EHVTL is influenced by various factors, one of which is the distance from the tower. The further a person is from EHVTL, the lower the intensity of the magnetic field received. In addition, time of day also plays an important role, as the magnetic field intensity tends to be higher at night when the electrical load is at its peak (Boukabou & Kaabouch, 2024). Other environmental factors, such as the presence of electrical equipment and vehicles, can also affect the magnitude of magnetic field exposure received.

Overall, exposure to ELF magnetic fields in the vicinity of the 500 kV EHVTL does have the potential to affect health, especially near the towers, where the magnetic field intensity is higher. Despite concerns about increased cancer risk and biological and behavioral changes observed in studies, the current evidence is not strong enough to draw definitive conclusions. Further research is needed to understand the long-term impacts of exposure to ELF magnetic fields around EHVTLs on human health.

Conclusion

Several research results prove that exposure to magnetic fields with an intensity of around 10 μT in vitro causes an impact of increasing cell proliferation. Increased cell proliferation in the human body can have negative effects on health. Increasing the intensity of ELF magnetic field exposure up to 170-234 times by 500 kV EHVTL compared to natural fields can cause biological effects at the cellular level and potentially cause health impacts for humans. Therefore, it is advisable to avoid living under the 500 kV EHVTL network, and the WHO recommendation that the threshold exposure value of 100 μT is declared safe for humans exposed for up to 24 hours/day needs to be reviewed. The results of this study are very useful as literacy in learning Science, namely in the Environmental Physics and Environmental Radiation courses.

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Author Contributions

Conceptualization, Sudarti and Sumardi.; methodology, Sudarti and Wahyu Muldayani; software, Tania Ardiani and Dina Helianti.; validation, Singgih Bektiarso and Ayu Munawaroh Aziz; formal analysis, Aditya Kurniawan.; investigation, Rio Dermawan; resources, Rio Dermawan.; data curation, Wahyu Muldayani; writing—original draft preparation, Sudarti; writing—review and editing, Rista Setiani; visualization, Aditya Kurniawan; supervision, Sumardi; project administration, Sudarti, Sumardi; funding acquisition, All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

All authors declare that they have no competing interests

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