Bio-Interaction Mechanism of Occupational Extremely Low-Frequency Magnetic Field and its Potential Effects on Human

Oyedum, Onyedi David[a], Nwohu, Mark Ndubuka[b], Ocheni, Abdullahi Ugbede Usman[c,*] and Moses, Abiodun Stephen[a]

[a]*Department of Physics, School of Physical Sciences, Federal University of Technology, Minna, Nigeria*

[b]*Department of Electrical and Electronics Engineering, School of Electrical Engineering and Technology, Federal University of Technology, Minna, Nigeria*

[c]*Department of Physics, Faculty of Physical Sciences, University of Maiduguri, Maiduguri, Nigeria*

Abstract

Human lifestyle is evolving as a result of advancements in technology which is mainly driven by electricity. The presence of extremely low-frequency magnetic fields in the Earth's atmosphere produced during the processes of generation, transmission and distribution of electricity in the occupational environment can penetrate human skin and is potentially hazardous to the health of exposed individuals, which has become a source of concern. This article presents the state of knowledge on the electrical and dielectric properties of human tissues, examines the various phenomena processes during the bio-interaction mechanism, and all-inclusive biological effects process and identifies potential health risks associated with prolonged and excessive exposure to the occupational magnetic field at extremely low frequency in addition to the underlining factors that influence the probable threats.

Keywords: *Bio-Interaction mechanism, Occupational ELF magnetic field, Health hazards, Human skin and Technogenic sources.*

1. Introduction

The rapid scientific revolution in the study of electricity and magnetism occurred during the 19th century [1]. However, the 20th century witnessed steady growth in the levels of technogenic sources of electromagnetic field (EMF) that pollute the Earth's atmosphere as a result of human social lifestyle and exponential technological developments [2–5]. These technogenic pollutants in the environment cannot be perceived neither sensed nor sniffed during exposure. But have far-reaching potential biological influence, and the associated health menaces have been of paramount problem for public health services and environmental organisations like the World Health Organization (WHO) and Environmental Health Trust [6]. The electropollution as a consequence of anthropogenic activities has exposed humans to different sources of fields, especially the extremely low frequency (ELF) magnetic field component that cannot be easily screened, but travels farther from the source when compared to the electric field counterpart [7].

* Corresponding author. Tel.: +234-805-0675473; Phone: +234-806-7092046
E-mail address: oauusman@unimaid.edu.ng

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The spectrum of electromagnetic fields is classified based on frequency as [8]: static field (SF), extremely low frequency (ELF) field, intermediate frequency (IF) field, radiofrequency (RF) field and microwave frequency field. However the research on biological effects, categorised electromagnetic fields primarily into two groups: ELF field and RF field due to extensive usage of electricity and various telecommunication systems respectively [9,10]. The electricity emission effects are observed at extremely low frequencies with high power, and the telecommunication emission effects are observed at very high frequencies with low power [11]. Thus, electrical power and related infrastructures are the predominant sources of the ELF fields [12,13], whereas telecommunication network equipment and radar installations are major sources of radio frequency fields [8,14].

Most literature has not elucidated the detailed processes involved in the interactive mechanism of human beings with a technogenic magnetic field from a utility environment. This article aims to bridge the gap by presenting an overview of the electrical and dielectric properties of human tissues that aid interaction. Consequently, leads to the insightful processes that occur during the bio-interaction mechanism of ELF magnetic field exposure. Also, the occupational ELF magnetic field from electrical power at its quasi-static state was delineated, and appraisal of the different categories of possible health consequences associated with the exposure in addition to an existing body of knowledge was discussed.

2. Methodology

An organised search using keywords: “Extremely low-frequency magnetic fields”, “Human electrical and dielectric properties”, “Electropollution”, “Biological effects associated with occupational magnetic field exposure”, “Influence of occupational magnetic field on human health”, “Biophysical mechanism of human exposure to magnetic field”, “Bio-interaction of human with magnetic field”, was performed in the archives of ResearchGate, PubMed Central, ScienceDirect and Academia to identify literature relevant to the article from 2013 to 2023. The articles on magnetic field at ELF exposure effects and biological mechanism of interaction were then categorised for appraisal.

3. Results and Discussion

3.1 Extremely low-frequency magnetic field

The region of low energy in the electromagnetic spectrum comprising AC field and other electromagnetic fields defined by frequencies from 0 Hz to 300 Hz is referred to as an extremely low-frequency field [15]. Power frequency at 50/60 Hz is the predominant source of the ELF fields [12]. These fields encountered by humans in the environment emanate from technogenic sources such as electrical equipment in switchyards, high-tension lines, electronics and residential appliances, connected to electrical power systems networks [4,16].

At ELF, electromagnetic fields are quasi-static in nature, which makes the components of time-varying electric field and magnetic field [17], propagate in perpendicular directions to each other [9] and studied independently from one another with variations of one not influencing the other and therefore, considered decoupled [18,19]. The ELF electric field is shielded by most materials with a high relative permittivity such as trees, and buildings [20,21] and by the human skin because of the low conductivity tissues that constitute the human biological system [22]. Moreover, the negligible electric field found above underground cable is due to the impeding capability offered by the outer layers of cable isolation and soil to the emitted field [23]. Based on the aforementioned reasons, the International Agency for Research on Cancer (IARC) [24], has classified ELF electric field as “inadequate scientific evidence (group 3)” of harmful effects [2]. Conversely, the ELF magnetic field is unimpeded except by materials that possess very high relative permeability [20], and easily penetrates biological human skin bodies without attenuation [19], due to the resemblance of its

permeability with that of humans [5]. Hence, interacts with the cell directly but because of inadequate polarisation, it causes various abnormalities in the cell membrane [15] such as more cell proliferation, less cell differentiation and apoptosis [25], and thus classified as “human carcinogen (group 2B)” and International Commission on Non-Ionising Radiation Protection (ICNIRP) have focus on assessing the level of health consequences linked with exposure [26]. The strength of the magnetic field is measured in Ampères per metre (A/m), but in terms of biological exposure, it is preferably expressed in Tesla (T).

3.2. Electrical properties of the human body

The inhomogeneous electrical properties of the different tissues that compose the human body are attributable to the varying water content of the tissues [27]. To assess the ELF field effects on humans, electrical properties such as the conductivity, permittivity and permeability of the biological tissues must be considered with respect to the external frequency of the field [28]. Permittivity is the intrinsic matter characteristic that determines the matter-electric interaction. It describes the medium capability to become polarised and store energy [29,30]. Permeability is the measure of the capability of tissue to aid the creation of the magnetic field within itself, and conductivity measures tissue's ability to conduct electricity and carry the electric signal [28]. However, conductivity and relativity permittivity are the electrical properties of human tissue that are functions of frequency and serve as significant parameters for determining non-ionising dosimetry [31,32].

The human body possesses very sensitive and complex electrochemical systems that contain electrical impulses and aid communication with the environment [33,34], due to the presence of little internal currents in the body [35]. The mobile charged particles contained in the body fluid have strong electrical conductivity [36], whose conductivity level within the system is determined by the ionic strength and viscosity [37]. Even in the absence of electromagnetic fields, the chemical reactions of charged particles in the fluid cause normal electrical currents in the human body to flow [3,38].

Two discrete migration phenomena ensue when an external magnetic field comes in contact with conductive body fluid; the first gives rise to accumulation on the body surface and forms an induced surface charge due to the electrolytic conductive nature of the tissues [39], while the second results to the induced charges, setting up an internally induced electric field which cancels the externally applied field [40]. The induced electric fields in the body, might affect the electrical properties of living cells and alter their function depending on the specific cell type [25], but the conductivities of various tissues have lesser impact [41]. Further findings by [39] have revealed that when biological tissues become conductive, positive and negative charges will migrate to the skin surface in response to the electric field. However, due to the unusual electrical properties, lower skin temperature has been found to decrease conductivity [42].

3.3. Dielectric properties of the human body

The human body has different dielectric properties that depend on the frequency of exposure, the biological tissue type [22,32], and temperature which makes it unstable [43]. The tissue's dielectric properties change with water content and age [8]. Hence, tissues with higher fluid content such as blood, muscle, liver and kidneys possessed higher electrical conductivity and dielectric constants (the ability of the body to store the field energy) than tissues such as fat and lungs [36].

The coupling mechanism of field-level interaction with the human body is determined by the dielectric properties of the tissues [42]. Specific conductivity and relative permittivity of tissue are the major dielectric properties to be considered in determining the response of tissues to electric stimulus. These properties influence the transmission, absorption and reflection capability of biological tissue's interaction with electromagnetic fields [44]. During the exposure process, the dielectric molecules will

be polarised and the extent of the polarisation is called permittivity. This permittivity is influenced by fluid and electrolyte contents [29].

3.4. Bio-interaction mechanism

Published studies in [4,9,45] stated that the level of the biophysical mechanism of interaction is a function of incident field frequency and polarisation, whereas the potential biological response is determined by the strength of the field exposure, dielectric properties and cell types. The phenomenon of the interaction of the field with the body is referred to as coupling [46]. The coupling of fields with humans is a form of inductance whereby the current in one system induces a voltage in another [47]. The two main resultant coupling mechanisms of interaction in the body are the induction of an electric field which might affect the electrical properties of living cells and alter their function; and the generation of oscillating current by induced electric fields that aid in the transfers of body energy, consequently increasing entire body temperature [41]. The body temperature rise stems from thermos molecular agitation during coupling when the tissue absorbs energy [48]. Therefore, the action mechanism of the ELF field is the induction of electromotive force and hence currents in conductive tissues [23]. So, when the body interacts with the ELF magnetic field, the strength and duration of exposure determine the induced electric field [49] and this induced field causes a temperature increase of body tissues and, the phenomenon is referred to as bio-electromagnetics [48]. The process leads to the activation of nerve cells [23], and the disorderliness of biomolecular structure altering the physiological functions of the system [49]. This disorderliness in the biological system is a result of an uneven distribution of ionic concentration in the different cells due to inadequate polarisation [26].

Faraday's principle states that the time-varying magnetic field sets up electric field production around the system [47]. During the bio-interaction mechanism, the induced electric field acts on the neutral dielectric molecules present within the system, alters the polarity of the biological molecules through splitting, and the formation of electric dipoles ensues from the displacement [49–51]. Thus, distort the existing biological processes [33]. Potential differences created by the fragmented molecules resulting from drifting in the opposite direction of the positive and negatively charged molecules cause the flow of current in the biological system [36,50,51]. The induced current distribution depends on incident wavelength, body location, distance and size, and the strength and duration of exposure to the ELF magnetic field [26,52].

The electric field induced in the biological system gives rise to surface charge because the bioelectric property's presence makes the system susceptible to electromagnetic field effects [53]. Hence, the normal physiological balance is disrupted when electric fields and circulating induced current, compete with endogenous current and voltage [33]. And once the threshold value in the particular body tissue is exceeded, instantaneous effects like stimulations of nerves and muscles occur [22], and permanent effects such as neurological and cardiovascular disorders, and low sperm count can occur [48,54]. However, the level of impact-induced electric field might have depends on the conductive nature of the medium.

3.4.1. Biological effects of ELF magnetic field exposure

The biological effect is a physiological response to field exposure, or changes in the environment [38], identified through both numerical modelling and simulations [55]. Environmental exposure to the ELF magnetic field is the main influential cause of biological effects because it interacts with the cell directly through the cell membrane [15]. The biological effects are associated with electric fields and current induction [6]. Time-varying magnetic field induction leads to two distinct induced currents in the system: an eddy current that circulates inside the body; and a current in/out of the body, which, could modify biological processes in the body because the induced eddy current is not grounded in the body [46], therefore stimulate excitable tissues at low frequencies in the body. The mechanism of induced current action in the body is what is referred to as stimulant action

and is measured in terms of current density [56]. The current density induced is an aftermath of the coupling of the external ELF magnetic field [35] and causes the distribution of current inside the body and most preferable dosimetry quantity at low frequency for evaluation of induction in biological system. Dosimetry is defined as the dose rate quantity due to external exposure [57]. The shape and dimensions of the body, with its orientation with respect to the incident field, are factors that determine coupling [46]. It is worth noting that current density and electric field induction have greater coupling when the body direction to the exposed ELF magnetic field is from front to back [10].

Biological effects have become a significant and frequently explored area owing to likely risks such as electric shock and tissue burns posed on persons exposed to ELF magnetic field [58,27]. The effects result in detrimental changes by force alteration of ions and molecules in the cell, thereby altering the cell membrane potential [15]. But, the mechanism for potential adverse biological effects remains controversial [10,59], due to inconclusive independent experiments validating the epidemiological findings that exposure to ELF magnetic field is the cause of adverse health consequences [60]. However, a study by Swanson and Kheifets (2006) pointed out that no potential mechanisms and aftermath biological effects of ELF magnetic fields are unlikely to occur in order of 1 μT [61]. Nonetheless, these effects on the human body are distinguished based on the duration of exposure: long-term (cumulative) exposure or short-term (acute) exposure [18], which depend on the electric properties of biological tissues during exposure [39,43]. These effects arise when there is excitation of the biological neurons and muscles [56]. Thus, its influence in the biological system often becomes obvious in the form of physiological, organic or social changes in response to induced field. But, the observation of biological effects, does not certainly suggest the presence of biological hazards. All the same, it may occasionally lead to a detrimental health disorder [48,62] if it strains the system for a longer period and therefore causes permanent damage [3].

3.4.2. Health effects of ELF magnetic field exposure

An adverse health effect is the source of measurable damage to the health of an unprotected person or that of the offspring [63]. Published kinds of literature have revealed that biological systems are sensitive to incident time-varying magnetic fields and this can affect basic life progress such as growth and development, orientation, structure and function of proteins, lipids, metabolic pathways, membranes, antioxidant defence and genetic material [64].

Epidemiological and experimental research have also made known that the likely effect of ELF magnetic field on humans might appear slow, but are continuous and cumulative [65]. The effects produced are distinguished basically into three different types: endocrine alterations, immune system damage and carcinogenic effects [66]. Therefore, the effects are distinctly characterised as short-term effects and long-term effects [11,67]. The principal causes of these effects are changes in melatonin secretion as a result of exposure to ELF magnetic fields. Since melatonin is an antioxidant and a scavenger of free radicals, the level of this hormone declines due to exposure. The processes of inhibitory effect to ELF field exposure that altered hormone production of melatonin that resulted in abnormalities can summarily be termed as “melatonin hypothesis” [7,31,33,52,59,68,69]. Table 1 presents the summary of probable health effects arising from exposure to ELF magnetic field based on the three different categories.

Table 1. Summary of ELF magnetic field exposure effects classification

ENDOCRINE ALTERATIONS EFFECTS		
	Underling causes	**Resultant effects**
References	**Occupational stress exposure effects**	
[27,67,69,70]	• overproduction of oxidative stress indexes such as nitric oxide in the brain	• Alter hypothalamic-pituitary-adrenal axis function, damage DNA, depression, anxiety and

		cognitive dysfunction
	• disturbance of the antioxidant system balance	• contribute to the ageing process
	Brain exposure effects	
[72,73,74]	• Temperature increase in brain tissues and measurable changes in brain electrical activity	• Influences the sensory perception, cognitive activities, sleep and mood. • Deterioration in memory and learning processes
IMMUNE SYSTEM EFFECTS		
	Sleeping quality exposure effect	
[27,67,70,78,79,80]	• Interference in the production of melatonin by the pineal gland in the brain	• Headaches, fatigue burnout, mental distress, anxiety and depression
	Reproductive system exposure effect	
[25,26,33,49,69, 75,76,77]	• Regulation of reproductive hormones level, sensitivity and vulnerability of the male reproductive system to temperature increase and decrease human sperm parameters	• Reduction in testosterone levels, • Affects sexual cells and sexual desire, • High-risk miscarriage during pregnancy
CARCINOGENIC EFFECTS		
	Leukaemia exposure effect	
[79,81,82]	• Prolonged adult occupational exposure, excessive children exposure, maternal exposure during pregnancy	• Prevalence of acute myeloid leukaemia (AML) • Prevalence of childhood acute lymphoblastic leukaemia (ALL) • Affect germ cells • Affect fetal progress
	Brain tumour exposure effect	
[80,83]	• Prolonged and excessive occupationally exposed adults	• Development of glioma • Risk of meningioma • Parotid cancer

4. Conclusions

This article has appraised the ELF magnetic field that pollutes the environment and elicited the intensity and duration of exposure during daily encounters to influence the induction of fields with the biological system. The elucidated electrical properties (conductivity, permeability and permittivity) and dielectric properties of the human tissue response have brought to spotlight the interaction mechanism that occurs in the biological system during the processes of induction and the underlining phenomena of biological alteration. The aftermath of possible health risks associated with prolonged and excessive exposure was reviewed and classified as a contribution to existing literature studies.

Conflict of Interest

We declare no conflict regarding the publication of the study.

References

[1] Redlarski, G., Lewczuk, B., Zak, A., Koncicki, A., Krawczuk, M., Piechocki, J., Jakubiuk, K., Tojza, P., Jaworski, J., Ambroziak, D., Skarbek, A., & Gradolewski, D. (2015). The influence of electromagnetic pollution on living organisms: Historical trends and forecasting changes, *BioMed Research International*, pp. 1–18. http://dx.doi.org/10.1155/2015/234098

[2] Ocheni, A. U. U., Oyedum, O. D., Nwohu, M. N., & Moses, A. S. (2023, February). Occupational exposure levels of ELF magnetic field assessment in 330 kV switchyard of hydro-plant and gas-plant stations in North-Central Nigeria, In *Proceedings of the NIPES-NCEE 2ND International Conference 15-17th February 2023*, 351–360. www.nipesjournals.org.ng

[3] Velentza, O. (2015). Electromagnetic pollution - Pathological effects of electromagnetic fields in man, *American Association for Science and Technology Journal of Health (AASCIT Journal of Health), 2*(6), 74–79. http://www.aascit.org/journal/health

[4] Vila, J., Bowman, J. D., Richardson, L., Kincl, L., Conover, D. L., McLean, D., Mann, S., Vecchia, P., Tongeren, M., & Cardis, E. (2016). A source-based measurement database for occupational exposure assessment of electromagnetic fields in the INTEROCC study: A literature review approach, *Annals of Occupational Hygiene, 60*(2), 184–204. https://doi.org/10.1093/annhyg/mev076

[5] Ocheni, A. U. U., Oyedum, O. D., Nwohu, M. N. & Moses, A. S. (2023). Analysis of magnetic field exposure at extremely low frequency (ELF) in 330kV Transmission Switchyards, *Journal of Materials Engineering, Structures and Computation 2*(2), 12–19. www.nipesjournals.org.ng

[6] Warillea, A. A., Altun, G., Elamina, A. A., Kaplan, A. A., Mohameda, H., Yurt, K. K. & El-Elhaj, A. (2017). Skeptical approaches concerning the effect of exposure to electromagnetic fields on brain hormones and enzyme activities, *Journal of Microscopy and Ultrastructure, 5*, 177–184. http://dx.doi.org/10.1016/jmau.2017.09.002

[7] Abarghoee, S. E., Halvani, G. H., Kargar-Shouroki, F., Mihanpour, H., & Madadizadeh, F. (2022). Job stress among workers exposed to extremely low frequency electric and magnetic fields in a combined cycle power plant, *Journal of Environmental Health and Sustainable Development (JEHSD), 7*(2), 1614–1622. http://dx.doi.org/10.18502/jehsd.v7i2.9785

[8] Vergallo, C. & Dini, L. (2018). Comparative analysis of biological effects induced on different cell types by magnetic fields with magnetic flux densities in the range of 1–60 mT and frequencies up to 50 Hz, *Sustainability, 10*(2776), 14. http://doi.org/10.3390/su10082776

[9] Hamedani, B. G., Goliaei, B., Shariatpanahi, S. P., & Nezamtaheri, M. (2022). An overview of the biological effects of extremely low frequency electromagnetic fields combined with ionising radiation, *Progress in Biophysics and Molecular Biology, 172*, 50–59. https://doi.org/10.1016/j.pbiomolbio.2022.04.008

[10] Singh, S. & Kapoor, N. (2014). Health implications of electromagnetic fields, mechanisms of action, and research needs, *Advances in Biology*, 1–25. http://dx.doi.org/10.1155/2014/198609

[11] Raghu, N., Krishna, M., Nagendra, K., & Trupti, V. N. (2015). Measurement and study of radiation levels and its effects on living beings near electrical substations, *The Journal of CPRI*, 11(3), 469–474. https://www.cprijournal.in/index.php/pr/article/view/703

[12] Lai, J. Zhang, Y., Zhang, J., Liu, X., Ruan, G., Chaugai, S., Tang, J., Wang, H., Chen, C. & Wang, D. W. (2016). Effects of 100-μT extremely low frequency electromagnetic fields exposure on hematograms and blood chemistry in rats, *Journal of Radiation Research, 57*(1), 16–24. https://dx.doi.org/10.1093/jrr/rrv059

[13] Vulević, B., Grbić, M., & Osmokrović, P. (2014). Survey of ELF electric and magnetic field levels – One example for determining of the measurement uncertainty," *Journal of Radioprotection Research, 2*(2), 10–14. http://doi.org/10.12966/jrr.06.02.2014

[14] Rianne, S. (2018). Comparison of international policies on electromagnetic fields (power frequency and radiofrequency fields), *National Institute for Public Health and the Environment*, RIVM, BA Bilthoven, Netherlands.

[15] Sudarti, Nuraini, L., Saleh, T. A., & Prihandono, T. (2018). The analysis of extremely low frequency (ELF) electric and magnetic field exposure biological effects around medical equipments, *International Journal of Advanced Engineering Research and Science (IJAERS), 5*(7), 289–296. https://doi.org/10.22161/ijaers.5.7.37

[16] Popoola, J. J., Adua, M. R., & Itodo, E. S. (2021). Assessment of possible health risks potential of electromagnetic fields from high voltage power transmission lines in Akure, Nigeria, *Journal of Applied Science & Process Engineering, 8*(1), 684–699. https://doi.org/10.33736jaspe.v8i1

[17] Özkaya, U., Seyfi, L., & Yaldiz, E. (2018). Analysis of electromagnetic radiation in daily life, *Paper Presented in 2nd International Symposium on Innovative Approaches in Scientific Studies*, Samsun, Turkey.

[18] Costea, M., Golovanov, N., Grinţescu, I. M., Stănciulescu, E., & Gheorghe, S. (2014). Human exposure to electromagnetic fields produced by distribution electric power installations, *Advances in Electrical and Computer Engineering, 14*(1), 29–36. www.aece.ro

[19] Halgamuge, M. N., Abeyrathne, C. D., & Mendis, P. (2011). Analysis of biological effect of AC-DC electromagnetic fields using the Lorenz model, *Biomedical Engineering and Information Systems: Technologies, Tools and Applications*, Hershevy PA 17033, Medical Information Science Reference (an imprint of IGI Global), 31–53. https://doi.org/10.4018/978-1-61692-004-3.ch002

[20] Al-Badi, A. H. (2012). Measurement and analysis of extremely low frequency electromagnetic field exposure in Oman, *Journal of Electromagnetic Analysis and Applications, 4*, 1–7. http://www.SciRP.org/journal/jemaa

[21] Ali, K. J., Hasan, G. T., & Ahmed, A. M. (2017). Investigate and analyze the electromagnetic field levels inside an electric power substations, *Tikrit Journal of Engineering Sciences, 24*(3), 10–14. http://dx.doi.org/10.25130/tjes.24.3.02

[22] Stuchly, M. A. (2002). Biological effects of electromagnetic fields, *International Journal of Bioelectromagnetism, 4*(2), 157–160. http://www.ijbem.org/volume4/number2/0.66.htm

[23] Pophof, B., Henschenmacher, B., Kattnig, D. R., Kuhne, J., Vian, A., & Ziegelberger, G. (2022). Biological effects of elctric, magnetic, and electromagnetic fields from 0 to 100 MHz on fauna and flora: Workshop report, *Health Physics*, Munich, Germany. http://doi.org/10.1097/HP.0000000000001624

[24] Roldán-Blay, C., & Roldán-Porta, C. (2020). Quick calculation of magnetic flux density in electrical facilities, *Applied Sciences, 10*(891). http://doi.org/10.3390/app10030891

[25] Tian, H., Zhu, H., Gao, C., Shi, M., Yang, D., Jin, M., Wang, F., & Sui, X. (2023). System-level biological effects of extremely low-frequency electromagnetic field: an *in vivo* experimental review, *Frontiers in Neuroscience*. 17:1247021. http://doi.org/10.3389/fnins.2023.1247021

[26] Suri, S., Dehghan, S. F., Sahlabadi, A. S., Ardakani, S. K., Moradi, N., Rahmati, M., & Tehrani, F. R. (2020). Relationship between exposure to extremely low-frequency (ELF) magnetic field and the level of some reproductive hormones among power plant workers, *Journal of Occupational Health*, 62(e12173). http://doi.org/10.1002/1348-9585.12173

[27] Bidi, M. (2020). Biological risk assessment of high-voltage transmission lines on worker's health of electric society., *Polska Akademia Nauk*: *Archives of Electrical Engineering*, 69(1), 57–68. http://doi.org/10.24425/aee.2020.131758

[28] Haque, M. E., Suman, A. A., & Rashid, M. M. (2012). Numerical evaluation of specific absorption rate and skin depth on human body tissue due to electromagnetic field emitted from mobile phone antenna, In *Proceedings of the International Conference on Electrical, Computer and Telecommunication Engineering 01- 02 December 2012 (ICECTE2012), RUET*, Rajshahi-6204, Bangladesh.

[29] Inan, U. S. (1999). *Engineering Electromagnetic*, menlo Park: Addisson Wesly.

[30] Wu, T., Rappaport, T. S., & Collins, C. M. (2015). The human body and millimeter-wave wireless communication systems: Interactions and implications, *Paper Present in 2015 IEEE International Conference on Communications (ICC)*, London, UK.

[31] Ates, K., Carlak, H. F., & Ozen, S. (2018). Exposure analysis of a human body due to underground power cables and magnetic field mitigation," *Paper Presented in International Conference on Advanced Technologies, Computer Engineering and Science (ICATCES'18)*, Safranbolu, Turkey, 2018.

[32] Husni, N. A., Islam, M. T., Faruque, M. R. I., & Misran, N. (2013). Effects of electromagnetic absorption towards human head due to variation of its dielectric properties at 900, 1800 and 1900 MHz with different antenna substrates," *Progress In Electromagnetics Research, 138*, 367–388. http://doi.org/10.1515/secm-2012-0024

[33] Adah, A. S., Adah, D. I., Biobaku, K. T., & Adeyemi, A. B. (2018). Effects of electromagnetic radiations on the male reproductive system, *Anatomy Journal of Africa, 7*(1), 1152–1161. http://doi.org/10.4314/aja.v7i1.169488

[34] Al-Faqeeh, I. J., Abu-Jafar, M., & Abdelraziq, I. R. (2015). The effect of the electromagnetic radiation from high voltage transformers on students health in Hebron district, *International Journal of Geology, Agriculture and Environmental Sciences*, *3*(1), 75–81. www.woarjournals.org/IJGAES

[35] Ocheni, A. U., & Usman, A. (2015). Assessment of magnetic field effects and estimation of associated current density of electrical injection substations in Kano metropolis," *Advances in Physics Theories and Applications*, *50*, 1–6. www.iiste.org

[36] Fan, X. Zhou, Q., Liu, Z., & Xie, F. (2015). New derivation method and simulation of skin effect in biological tissue, *Bio-Medical Materials and Engineering 26*, S429–S437. http://doi.org/10.3233/BME-151332

[37] Yalçın, S., & Erdem, G. (2012). Biological effects of electromagnetic fields," *African Journal of Biotechnology*, *11*(17), 3933–3941. http://doi.org/10.5897/AJB11.3308

[38] Nimbalkar, V. S. (2015). Biological effects of ELF on human body cells," *International Journal of Scientific & Engineering Research, (IJSER)*, *6*(7), 1520–1520. http://www.ijer.org

[39] Siriwitpreecha, A., & Rattanadecho, P. (2019). Numerical analysis of biological effects on several organs inside human body exposed to electric field from 500 kV OHTLs," *Songklanakarin J. Sci. Technol.*, *41*(3), 649–657. http://www.sjst.psu.ac.th

[40] Sadiku, N. O. M. (1989). *Elements of Electromagnetics*, 3rd ed., Philadelphia, US: Saunders.

[41] Stam, R. (2014). The revised electromagnetic fields directive and worker exposure in environments with high magnetic flux densities," *Annal of Occupational Hygiene*, *58*(5), 529–541. http://doi.org/10.1093/annhyg/meu-010

[42] Hershkovich, H. S., Urman, N. Yesharim, O. Naveh, A., & Bomzon, Z. (2019). The dielectric properties of skin and their influence on the delivery of tumor treating fields to the torso: A study combining in-vivo measurements with numerical simulations," *Physics in Medicine and Biology*, *64*(185014), 15. DOI 10.1088/1361-6560/ab33c6

[43] Gun, L., Ning, D., & Liang, Z. (2017). Effective permittivity of biological tissue: Comparison of theoretical model and experiment," *Mathematical Problems in Engineering*, 7. http://doi.org/10.1155/2017/7249672

[44] Porter, E., Gioia, A. L., Santorelli, A., & Halloran, M. O. (2017). Modeling of the dielectric properties of biological tissues within the histology region. *IEEE Transactions on Dielectrics and Electrical Insulation*, 24(5), 3290–3301. http://dx.doi.org/10.1109/TDEI.2017.006690

[45] Fiocchi, S., Chiaramello, E., Parazzini, M., & Ravazzani, P. (2018). Influence of tissue conductivity on foetal exposure to extremely low frequency magnetic fields at 50 Hz using stochastic dosimetry, *PLoS ONE*, *13*(2), e0192131. http://doi.org/10.1371/journal.pone.0192131

[46] Ponnle, A. A., & Ani, S. K. (2019). Assessment of exposure to indoor power frequency magnetic fields: SEET building and engineering laboratories, FUTA," *Journal of Engineering and Engineering Technology*, *13*, 103–117. https://www.futajeet.com

[47] Ross, C. L., Siriwardane, M., Almeida-Porada, G., Porada, C. D., Brink, P., Christa, G. J., & Harrison, B. S. (2015). The effect of low-frequency electromagnetic field on human bone marrow stem/progenitor cell differentiation," *Stem Cell Research*, *15*, 96–108. http://doi.org/10.1016/j.scr.2015.04.009

[48] Aliyu, O., Maina, I., & Ali, H. (2012). Analysis of electromagnetic pollution due to high voltage transmission lines, *Journal of Energy Technologies and Policy*, *2*(7), 1–10. www.iiste.org

[49] Verma, S. Gupta, A., & Kumar, B. (2019). Interaction of radiofrequency radiation with biological systems: A comprehensive update on recent challenges, *Defence Life Science Journal*, *4*(2), 83–90. http://doi.org/10.14429/dlsj.4.13383

[50] Kulkarni, G., & Gandhare, W. Z. (2012). Proximity effect of high voltage transmission lines on humans, *ACEEE International Journal on Electrical and Power Engineering*, *3*(1), 28–32. http://doi.org/01.IJEPE.03.01.11

[51] Özen, S. (2008). Low-frequency transient electric and magnetic field coupling to child body, *Radiation Protection Dosimetry*, *128*(1), 62–67. doi:10.1093/rpd/nc-m315

[52] Bakker, J. F., Paulids, M. M., Neufeld, E., Christ, A., Chen, X. L., Kuster, N., & van-Rhoon, G. C. (2012). Children and adults exposed to low-frequency magnetic fields at the ICNIRP reference levels: Theoretical assessment of the induced electric fields, *Physics in Medicine and Biology*, *57*, 1815–1829.

[53] Huang, J., Tang, T., Hu, G., Zheng, J., Wang, Y., Wang, Q., Su, J., & Zou, Y. P. X. (2013). Association between exposure to electromagnetic fields from high voltage transmission lines and neurobehavioral function in children," *PLoS ONE* , *8*(7), e67284. http://doi.org/10.1371/journal.pone.0067284

[54] Bhattacharjee, S. (2014). Protective measures to minimize the electromagnetic radiation, *Advance in Electronic and Electric Engineering*, *4*(4), 375–380. http://www.ripublication.com/aeee.htm

[55] Lovat, G., & Celozzi, S. (2006). A six-loop magnetic-field exposure system for extremely low-frequency applications, *IEEE Transactions on Magnetics*, 42(8), 1982–1990. https://doi/10.1109/TMAG.2006.877109

[56] Osaigbovo, I. A., & Isabona, J. (2018). Current density and SAR analysis of biological tissues due to radiant electromagnetic waves from base station antennas, *International Journal of Advanced Research in Physical Science (IJARPS)*, *5*(11), 15–23. www.arcjournals.org

[57] IEEE, International Committee on Electromagnetic Safety, (2019). IEEE standard for safety levels with respect to human exposure to electric, magnetic, and electromagnetic fields, 0 Hz to 300 GHz," IEEE Std C95.1-2005/ Incorporates IEEE Std C95.1-2019/Cor 1-2019, IEEE 3 Park Avenue New York, NY 10016-5997 USA.

[58] Klimek, & Rogalska, J. (2021). Extremely low-frequency magnetic field as a stress factor—really detrimental?—insight into literature from the last decade., *Brain Sciences*, 11(174). http://doi.org/10.3390/brainsci1102017

[59] Zhang, Z.-Y., Zhang, J., Yang, C.-J., Lian, H.-Y., Yu, H., Huang, X.-M., & Cal, P. (2016). Coupling mechanism of electromagnetic field and thermal stress on drosophila melanogaster, *PLoSONE*, *11*(9), e0162675. http://doi.org/10.1371/journal.pone.0162675

[60] Hore, P. J. (2019). "Upper bound on the biological effects of 50/60 Hz magnetic fields mediated by radical pairs," *eLIFE*, 20. https://doi.org/10.7554/eLife.4417

[61] Kwan-Hoong, N. (2003). Non-ionising radiation-sources, biological effects, emissions and exposure, In *Proceedings of the International Conference on Non-Ionising Radiation at UNITEN (ICNIR 2003). Electromagnetic Fields and Our Health*, Kuala Lumpur, Malaysia.

[62] International Commission on Non-Ionizing Radiation Protection (ICNIRP), (1998). ICNIRP Guidelines for Limiting Exposure to Time-varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz), *Health Physics*.

[63] Ahuja, Y. R., Sharma, S., & Bahadur, B. (2013). Autism: An epigenomic side-effect of excessive exposure to electromagnetic fields," *International Journal of Medicine and Medical Sciences*, *5*(4), 171–177. http://doi.org/10.5897/IJMMS12.135

[64] Nur, A. A., Suryandari, D. A., & Sari, P. (2018). Effect of extremely low frequency electromagnetic field exposure on pachytene spermatocyte cell quantity in Webster strain male mice, *Presented in the 2nd Physics and Technologies in Medicine and Dentistry Symposium*.

[65] Macrì, M. A., DI Luzio, S., & DI Luzio, S. (2002). Biological effects of electromagnetic fields, *International Journal of Immunopathology and Pharmacology*, *15*(2), 95–105. http://doi.org/10.1177/039463200201500204

[66] Jayalakshmi, N. Y., & Deepa, S. N. (2016). Modelling of electric and magnetic fields under high voltage AC transmission line, *IOSR Journal of Electrical and Electronics Engineering*, *11*(3), 24–31. http://doi.org/10.9790/1676-1103042431

[67] Bagheri, M. H., Khanjani, N., Ebrahimi, M. H., Mousavi, S. H., & Nazarkhani, F. (2020). Investigating the effects of exposure to extremely low frequency electromagnetic fields on job burnout syndrome and the severity of depression; the role of oxidative stress, *Journal of Occupational Health*, 1–8. http://doi.org/10.1002/1348-9585.12136

[68] Touitou, Y., & Selmaoui, B. (2012). The effects of extremely low-frequency magnetic fields on melatonin and cortisol, two marker rhythms of the circadian system, *Dialogues in Clinical Neuroscience*, *14*(4), 381–399. https://dx.doi.org/10.31887/DCNS.2012.14.4/ytouitou

[69] Asgari, A., Shoja, E., & Barzegar, S. (2019). The effect of electromagnetic waves and workplace lighting on job stress in employees of power distribution company, *Pakistan Journal of Medical and Health Sciences*, *13*(2), 889–892.

[70] Diaz-Del Cerro, E., Félix, J., Tresguerres, J. A. F., & Fuenta, M. D. L. (2022). Improvement of several stress response and sleep quality hormones in men and women after sleeping in a bed that protects against electromagnetic felds, *Environmental Health*, 21, 72. http://doi.org/10.1186/s12940-022-00882-8

[71] Shalaby, M., Shokair, M., & Messiha, N. W. (2018). Electromagnetic field measurement instruments: survey, *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, 43(1), 1–14. http://doi.org/10.1007/s40998-018-0116-y

[72] Capone, F., Pellegrino, G., Motolese, F., Rossi, M., Musumeci, G., & Di-Lazzaro, V. (2020). Extremely low frequency magnetic field do not affect LTP-like plasticity in healthy humans, *Frontiers in Human Neuroscience, 14*(14). https://doi.org/10.3389/fnhum.2020.00014

[73] Raghu, N., Krishna, M. N., Nagendra, K., & Trupti, V. N. (2017). Survey of electromagnetic field near EVH lines and their health hazards, Paper *Presented in International Conference on Smart Grids, Power and Advanced Control Engineering (ICSPACE2017)*, Bangalor, India.

[74] Barsam, T., Monazzam, M. R., Haghdoost, A. A., Ghotbi, M. R., & Dehghan, S. F. (2012). Effect of extremely low frequency electromagnetic field exposure on sleep quality in high voltage substations, *Iranian Journal of Environmental Health Science & Engineering*, 9(15). https://doi.org/10.1186/1735-2746-9-15

[75] Vaziri, M. H., Sadighi, G. M. A., Kavousi, A., Firoozeh, M., Khani J. R., Vosough T. D. A., Mohseni, H., Bagery, L. N., Azizi, M., & Salman, Y. R. (2011). The relationship between occupation and semen quality, *International Journal of Fertility & Sterility*. 5(2), 66–77. PMID:24963361; PMCID: PMC4059951

[76] Falahati, S. A., Anvari, M., & Khalili, M. A. (2011). Effects of combined magnetic fields on human sperm parameters, *Iranian Journal of Radiation Research, 9*(3), 195–200.

[77] Wdowiak, A., Mazurek, P. A., Wdowiak, A., & Bojar, I. (2017). Effect of electromagnetic waves on human reproduction, *Annals of Agricultural and Environmental Medicine, 24*(1), 13–18. http://doi.org/10.5604/123219-66.1228394

[78] Liu, H., Chen, G., Pan, Y., Chen, Z., Jin, W., Sun, C., Chen, C., Dong, X., Chen, K., Xu, Z., Zhang, S., & Yu, Y. (2014). Occupational electromagnetic field exposures associated with sleep quality: A cross-sectional study," *PLoS ONE, 9*(10), e110825. https://doi.org/10.1371/journal.pone.0110825

[79] Talibov, M., Olsson, A., Bailey, H., Erdmann, F., Metayer, C., Magnani, C., Petridou, E., Auvinen, A., Spector, L., Clavel, J., Roman, E., Dockerty, J., Nikkilä, A., Lohi, O., Kang, A., Psaltopoulou, T., Miligi, L., Vila, J., Cardis, E., & Schüz1, J. (2019). Parental occupational exposure to low-frequency magnetic fields and risk of leukaemia in the offspring: Findings from the Childhood Leukaemia International Consortium (CLIC). *Occupational and Environmental Medicine*, 76, 746–753. http://doi.org/10.1136/oemed-2019-105706

[80] Eskandani, R. & Zibaii, M. I. (2024). Unveiling the biological effects of radio-frequency and extremely-low frequency electromagnetic fields on the central nervous system performance. *BioImpacts*, *14*(4):30064. http://doi.org/10.34172/bi.2023.30064

[81] Huss, A., Spoerri, A., Egger, M., Kromhout, H., & Vermeulen, R. (2018). Occupational extremely low frequency magnetic fields (ELF-MF) exposure and hematolymphopoietic cancers – Swiss National Cohort analysis and updated meta-analysis. *Science Direct* https://www.elsevier.com/open-access/userlicense/1.0/

[82] Brabant, C., Geerinck, A., Beaudart, C., Tirelli, E., Geuzaine, C., & Bruyere, O. (2022). Exposure to magnetic fields and childhood leukaemia: A systematic review and meta-analysis of case-control and cohort studies. *Rev Environ Health*, 38(2), 229–253. http://doi.org/10.1515/reveh-2021-0112. PMID: 35302721

[83] Sahu, M., Behera, S. & Chattopadhyay, B. (2021). The influence of electromagnetic field pollution on human health: A systematic review. *Siriraj Medical Journal (SMJ), 73*(7), 485–492. http://dx.doi.org/10.33192/Smj.2021.63