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ORIGINAL ARTICLE

Health Impacts of Extremely Low-Frequency Electromagnetic Fields (ELF-EMFs): A Systematic Review of Recent Evidence (2015–2023)

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ABSTRACT

Background: Exposure to extremely low-frequency electromagnetic fields (ELF-EMFs) is pervasive due to modern reliance on electrical and electronic devices. This review examines the potential adverse health effects of ELF-EMFs based on studies published between 2015 and 2023. The investigation spans a range of health outcomes—including neurological, oncological, genetic, and mental health effects—while also highlighting research gaps and regional disparities.

Methods: A systematic review was conducted using the PubMed, Scopus, and Web of Science databases. Eligible studies included original research focused on ELF-EMFs and health outcomes. Data extraction covered study type, health effects, exposure magnitude, and geographical distribution. A total of 65 studies were analyzed and categorized into experimental, epidemiological, and case-control designs.

Results: The findings indicate significant associations between ELF-EMF exposure and conditions such as childhood leukemia, DNA damage, and oxidative stress. Mental health outcomes, including anxiety and depression, were frequently studied but yielded mixed results. Occupational exposure studies revealed potential risks, particularly among power plant workers and utility staff, while residential exposures were linked to neurobehavioral changes and sleep disturbances. Nevertheless, inconsistencies across studies hinder conclusive risk assessment.

Conclusion: While certain health risks of ELF-EMFs are well supported, substantial gaps remain in understanding less-studied effects, such as cardiovascular and endocrine disruptions. Future research should prioritize long-term, real-world exposures and address methodological limitations. These efforts are critical for informing public health guidelines and mitigating the potential risks associated with ELF-EMFs.

KEYWORDS: *ELF-EMFs, Health effects, DNA damage, Leukemia, Exposure assessment*

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INTRODUCTION

Exposure to extremely low-frequency (ELF) electromagnetic fields (EMFs) has become increasingly prevalent in recent years, primarily due to the widespread integration of electronic devices and electrical equipment into daily life [1]. This growing exposure has sparked significant scientific interest and heightened public concern regarding the potential health effects of ELF-EMFs. Defined as electromagnetic fields with frequencies ranging from 3 Hz to 300 Hz, ELF-EMFs are generated by various anthropogenic sources, including power lines, household appliances, and industrial machinery. Given the ubiquity of these sources, human exposure to ELF-EMFs is nearly unavoidable—raising pressing questions about their potential impact on human health [2].

Although immediate adverse effects from ELF-EMF exposure are rare, concerns persist regarding the implications of long-term exposure. Research has explored potential links between ELF-EMF exposure and various health conditions—such as sleep disturbances, headaches, anxiety, and depression—although definitive causal relationships remain elusive [3]. Notably, the International Agency for Research on Cancer (IARC) classifies ELF-EMFs as possibly carcinogenic to humans (Group 2B), citing evidence that long-term exposure may increase the risk of childhood leukemia and other cancers [4]. Proposed mechanisms for these effects include oxidative stress, disruptions in cellular signaling pathways, and altered melatonin production, all of which can impact circadian rhythms and immune function [5]. For instance, Ortega-Garcia et al. (2009) reported an elevated risk of childhood acute lymphoblastic leukemia associated with magnetic field exposure levels as low as 0.3–0.4 μT—well below the 100 μT threshold considered safe by the International Commission on Non-Ionizing Radiation Protection [6].

Occupational exposure to ELF-EMFs also raises significant concerns, particularly for workers in high-risk environments such as power plants, high-voltage facilities, and areas near transmission lines [7, 8]. Research on the health impacts of occupational ELF-EMF exposure has produced mixed results. Some studies have linked such exposure to an increased risk of brain tumors, notably gliomas [9]. Others have documented changes in oxidative stress markers and antioxidant enzyme activity among power plant workers [7]. Additionally, long-term occupational exposure has been associated with potential genotoxic effects and DNA damage [10]. Contradictory findings, however, complicate the narrative. For example, a study on workers exposed to ELF-EMFs generated by electromagnetic aircraft launch systems found no significant effects on thyroid function, immune function, or morphology over a three-year period [11]. Similarly, another investigation involving workers near transformers and distribution lines detected no significant neurobehavioral changes despite daily ELF-EMF exposure [12].

In summary, the debate surrounding the health effects of ELF-EMFs remains unresolved due to inconsistencies in the existing evidence. While some studies suggest potential health risks, others find no compelling indications of harm [13]. The scientific community continues to advocate for further research to improve health risk assessments and provide more definitive conclusions regarding ELF-EMF exposure [14]. This review aims to critically examine the global distribution of research, study methodologies, and reported adverse health effects. It also assesses the magnitude and sources of ELF-EMFs investigated in these studies to deepen our understanding of their potential health impacts and identify existing research gaps. By systematically evaluating the current body of evidence, this review seeks to inform ongoing discourse on ELF-EMFs and public health, offering valuable insights for policymakers, researchers, and healthcare professionals. Addressing these concerns is crucial for developing evidence-based guidelines and mitigating potential risks associated with ELF-EMF exposure in both occupational and residential settings.

MATERIALS AND METHODS

This systematic review examines studies conducted on the effects of ELF-EMFs on humans over the past six years (2015–2023), ensuring the review reflects the most recent and methodologically advanced evidence on the health impacts of ELF-EMFs. Comprehensive reviews and meta-analyses published prior to 2015, such as those by Kheifets et al. (2010) and Schüz et al. (2016), have already extensively covered earlier evidence on ELF-EMF-related health outcomes [15–17].

The search for eligible studies was conducted using the PubMed, Scopus, and Web of Science databases. The search strategy integrated key terms associated with ELF-EMFs and a range of health outcomes. The following outlines the search strategy applied in the Scopus database: TITLE((“ELF” OR “Magnetic

Fields” OR “extremely low frequency”) AND (“health effect” OR cancer OR “Leukemia” OR “Chronic disease” OR “DNA damage” OR “Cognitive effect” OR suicide OR “Oxidative stress” OR “Alzheimer” OR “Cardiovascular disease” OR “nervous disease” OR “nervous system” OR “cell damage” OR pregnancy OR fertility OR hereditary OR “fetal development” OR “depression” OR “Sleep disorder” OR “Neurodegenerative diseases” OR “Neurological effects” OR “Genetic effects” OR anxiety OR “Cellular effect” OR apoptosis) AND NOT (“clinical study” OR “Therapeutic”)).

We followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to conduct and report this systematic review. PRISMA is a widely recognized framework that ensures transparency, reproducibility, and completeness in systematic reviews. We adhered to the PRISMA checklist to structure the methodology, results, and discussion sections, and included a PRISMA flow diagram to visually represent the study selection process (Figure 1).

Our objective was to answer the following question: “What are the potential adverse health effects of exposure to extremely low-frequency electromagnetic fields (ELF-EMFs) based on evidence from studies published between 2015 and 2023?”. A PECO (“Participants,” “Exposure,” “Comparator,” and “Outcomes”) statement, which is used as an aid to developing a strategy for answering the study question, was developed. Our PECO statement was:

• Population: Humans (general population, occupational workers, and specific subgroups such as children or pregnant women).
• Exposure: Exposure to extremely low-frequency electromagnetic fields (ELF-EMFs).
• Comparator: Unexposed or low-exposed groups (depending on the study design).
• Outcome: Adverse health effects, including but not limited to:
• Neurological effects (e.g., Alzheimer’s disease, Parkinson’s disease, multiple sclerosis).
• Oncological outcomes (e.g., childhood leukemia, breast cancer).
• Genetic and cellular damage (e.g., DNA damage, oxidative stress).
• Mental health outcomes (e.g., anxiety, depression, sleep disturbances).

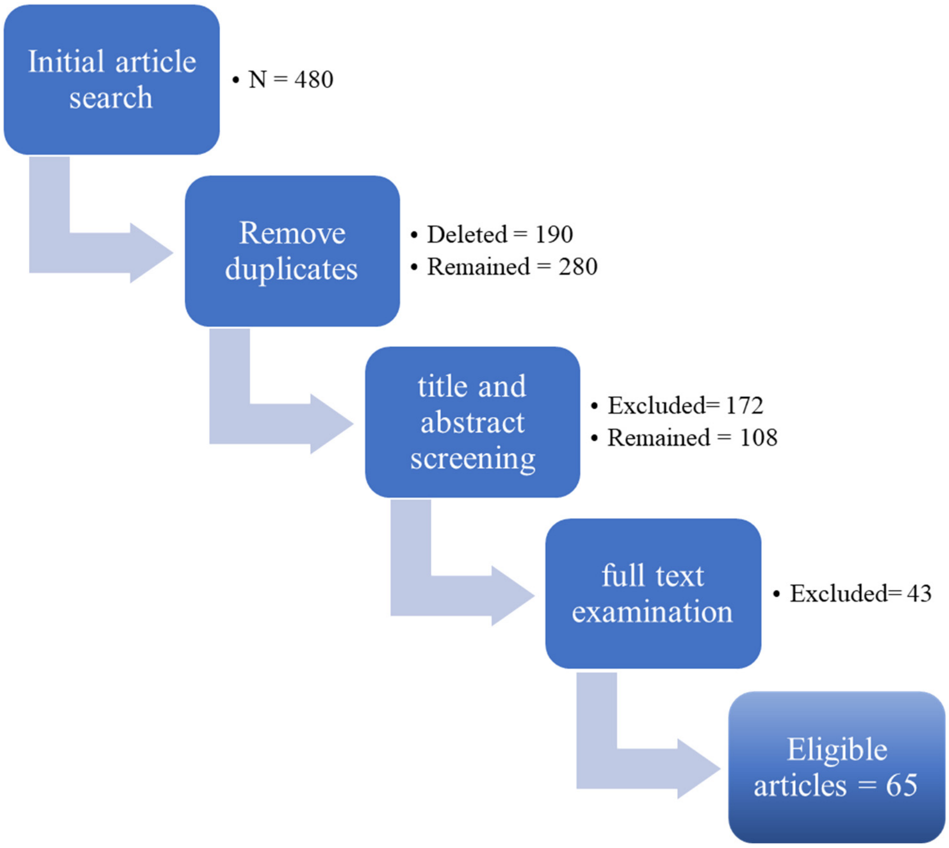

Figure 1. Flowchart illustrating the procedure for selecting eligible articles

• Reproductive and developmental effects (e.g., fertility issues, pregnancy-related outcomes).

Studies that met the following criteria were included in this review: the study was original and written in English; at least one of the investigated stressors was ELF-EMFs or a magnetic field; and the stressor demonstrated a correlation with the reported effects. Accordingly, clinical studies or therapeutic applications of ELF-EMFs, as well as reviews, editorials, conference abstracts, and letters to the editor, were excluded.

After identifying the main papers, additional sources were located using the "related articles" and "citations" functions in Google Scholar and ResearchGate. Reference lists of the primary studies were also screened to ensure thoroughness.

Data extraction was performed by two researchers, who independently screened the titles, abstracts, and full texts of the selected studies. They also independently extracted data using a standardized table. Disagreements were resolved through discussion or by consulting a third reviewer, minimizing subjective bias in study selection and data collection. Extracted data included the study title, year, study type, source type, type of effects, sample type, exposure magnitude, and country of origin. The third researcher cross-checked the two extracted datasets and resolved discrepancies by referring back to the original articles.

RESULTS

This section presents the findings from the systematic review, organized by the types of health effects associated with exposure to extremely low-frequency electromagnetic fields (ELF-EMFs). A considerable number of studies examined neurological effects, particularly those affecting the central and peripheral nervous systems, with a focus on conditions such as Alzheimer's disease, Parkinson's disease, and multiple sclerosis. While the majority of these investigations suggest a potential association between long-term ELF-EMF exposure and neurodegenerative disorders, the evidence remains inconclusive. Additionally, several studies explored the relationship between ELF-EMF exposure and mental health outcomes, including anxiety, depression, and sleep disturbances. These effects are well documented, with anxiety and depression among the most frequently studied conditions. Experimental studies have also reported instances of memory impairment and attention-deficit/hyperactivity disorder (ADHD).

The review identified a substantial number of studies investigating oncological outcomes, with particular emphasis on leukemia and breast cancer. Childhood leukemia emerged as a primary focus across many of these investigations. Additionally, ELF-EMF exposure has been associated with various forms of genetic and cellular damage. Findings related to DNA damage, apoptosis, alterations in gene expression, and oxidative stress suggest potential biological mechanisms underlying the health risks linked to ELF-EMF exposure, as summarized in Table 1.

Figure 2 illustrates the distribution of adverse effects associated with ELF-EMF exposure as reported in the reviewed studies. The abscissa represents the number of studies investigating each specific effect. Among the reported outcomes, DNA damage and leukemia are the most extensively studied, with the highest number of publications focusing on these areas. Anxiety and oxidative stress also emerge as frequently explored effects, followed by investigations into memory impairments and cellular effects. Other notable areas include sleep disorders, pregnancy-related outcomes, and fertility, which also receive significant attention in the literature. Conversely, topics such as ADHD, apoptosis, and hepatic effects are the least studied, indicating potential gaps in the research. The figure underscores a prioritization of neurological, genetic, and oncological effects while highlighting the need for further exploration of less frequently investigated outcomes, such as cardiovascular and endocrine-related effects.

Research activity is predominantly concentrated in North America, Europe, and Asia, reflecting differing levels of scientific engagement and regulatory focus, as illustrated in Figure 3. This figure presents the geographical distribution of the studies included in this review. In Asia, countries such as Iran and China have made substantial contributions to understanding the impacts of extremely low-frequency electromagnetic fields (ELF-EMFs), with a particular emphasis on residential exposures and their public health implications. In the United States and several European countries, including Germany and Denmark, extensive research has focused primarily on occupational exposures.

Epidemiological studies, which account for approximately half of the total literature, provide valuable insights into population-level trends. However, they often encounter challenges such as

Table 1. Studies Investigating the Health Outcomes of Exposure to ELF-EMFs

Affective systems	Adverse effect	References
Neurological Effects	Central or Peripheral Nervous System	[18-20]
	Alzheimer's disease	[21-23]
	Parkinson's disease	[20]
	Multiple sclerosis	[20, 21]
	Vertigo	[24]
Mental Health & Behavioral Disorders	Anxiety	[25-33]
	Depression	[24, 26, 29, 34]
	Stress	[19, 26]
	Occupational burnout syndrome	[34]
	Sleep disorder	[20, 26, 35]
	ADHD	[36]
	Memory impairment	[28, 31, 32, 37, 38]
Oncological Effects	Leukemia	[39-48]
	Breast cancer	[49-51]
	Skin cancer	[52]
Genetic and Cellular Damage	DNA damage	[53-66]
	Apoptosis [programmed cell death]	[35]
	Gene expression changes	[29]
	Oxidative stress	[28, 31, 57, 66-69]
	General cellular impact	[7, 70-72]
Hormonal and Endocrine Effects	Endocrine system disruption	[57, 61]
Reproductive Health	Fertility issues	[73-75]
	Pregnancy-related effects	[74, 76, 77]
Cardiovascular System	Hypertension	[24]
Hepatic (Liver) System	Hepatic effects	[78]
Musculoskeletal System	Musculoskeletal disorders	[79]
Other Health Concerns	Vitamin deficiency	[78]

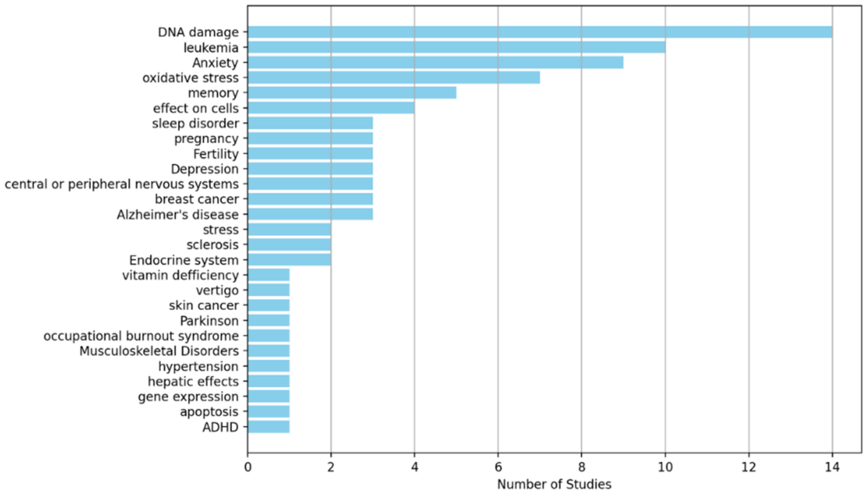

Figure 2. Distribution of Adverse Effects in the Studies

exposure misclassification and confounding variables. In contrast, experimental studies offer controlled environments that facilitate the investigation of causal mechanisms, particularly at the cellular and molecular levels. While case-control studies are useful for identifying associations, they may be susceptible to recall bias—especially when evaluating long-term ELF-EMF exposure. Notably, the majority of the reviewed studies (55%) fall under experimental designs, whereas case-control studies represent the smallest proportion (2%). Figure 4 categorizes the studies based on their methodologies, including epidemiological, experimental, and case-control designs.

Figure 5 illustrates the distribution of studies examining the health effects of extremely low-frequency electromagnetic fields (ELF-EMFs), categorized by study design and exposure source. As previously

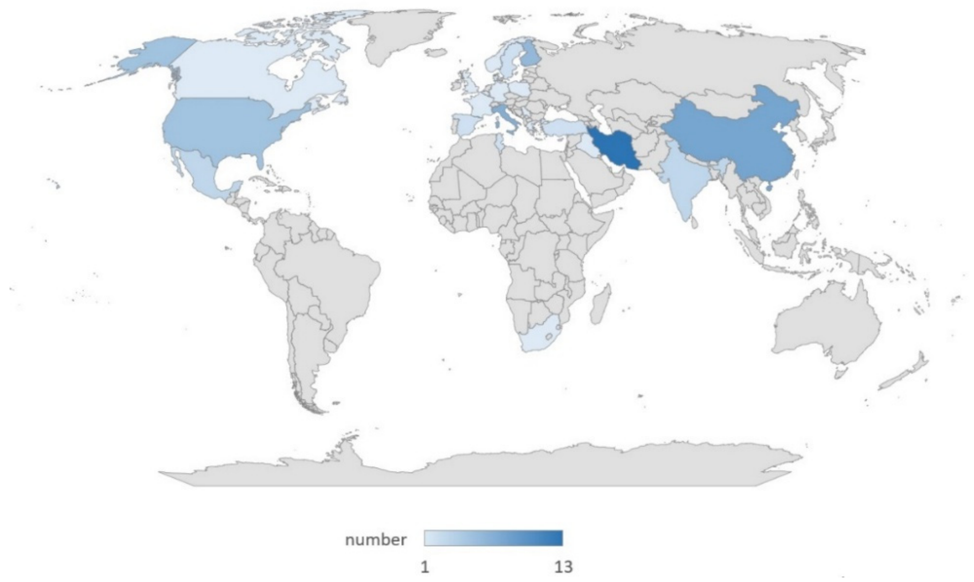

Figure 3. Geographical Distribution of the Studies

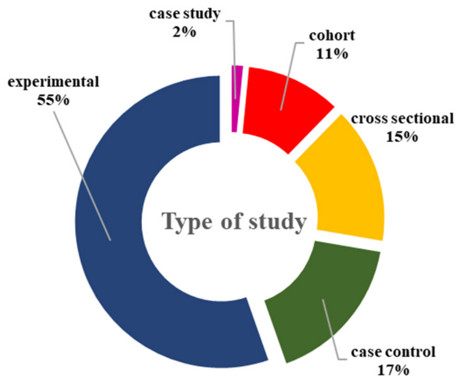

Figure 4. Distribution of Study Designs Included in the Systematic Review

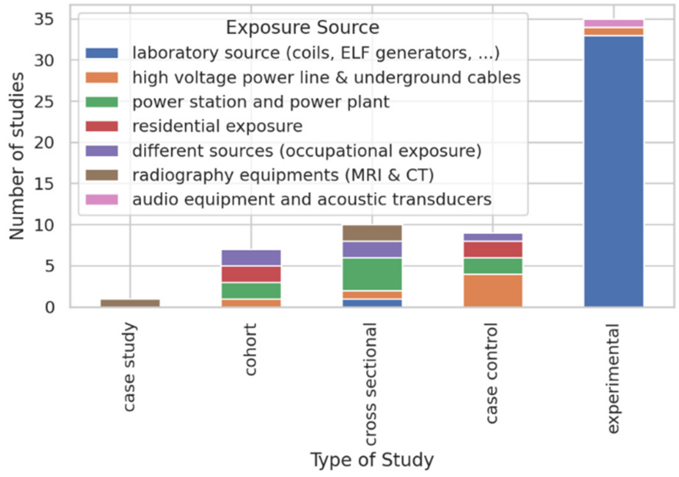

Figure 5. Source of ELF-EMF in Different Study Types

noted, experimental studies predominate, with most utilizing laboratory sources such as ELF generators or coils. This trend underscores a strong emphasis on controlled environments to establish causal relationships. In contrast, cohort, cross-sectional, and case-control studies show similar distributions across various real-world exposure contexts, including high-voltage power lines, power stations, residential settings, and occupational sources. This highlights the importance of investigating ELF-EMF effects in everyday environments. Notably, occupational exposure is particularly prominent in observational studies, indicating potential risks associated with workplace settings. Additionally, only one case study involved radiography equipment, suggesting a lack of comprehensive clinical reports in this domain.

The data reveal that laboratory sources—such as ELF generators and coils—dominate the research landscape, with the majority of studies focusing on field strengths within the range of 10^2–10^3 µT. Figure 6 presents the distribution of extremely low-frequency electromagnetic field (ELF-EMF) sources, categorized by magnetic field strength along with the corresponding number of studies for each source.

A significant portion of the research focuses on DNA damage, gene expression, and cellular effects—particularly within the 101 µT–1 mT and 1 mT–10 mT ranges—as illustrated in Figure 7. This emphasis reflects concern regarding the potential impact of moderate to high ELF-EMF exposures on fundamental biological processes.

Oxidative stress studies are distributed across a broad range of field strengths, with notable peaks at 1–10 µT and 11–100 µT. These patterns indicate that even low-intensity fields are actively investigated for their potential to induce oxidative damage.

Childhood leukemia research is concentrated in the 0.1–1 µT range, reflecting the relevance of low-level, everyday exposures. Studies on cancer—including breast cancer, leukemia, and melanoma—are distributed across multiple field strengths, with notable peaks at both 0.1–1 µT and 1 mT–10 mT. Research on anxiety, depression, ADHD, and cognitive effects is primarily clustered within the moderate field strength range (1 mT–10 mT), indicating growing scientific interest in the potential impact of ELF-EMFs on mental health and cognitive function.

DISCUSSION

Research on extremely low-frequency electromagnetic

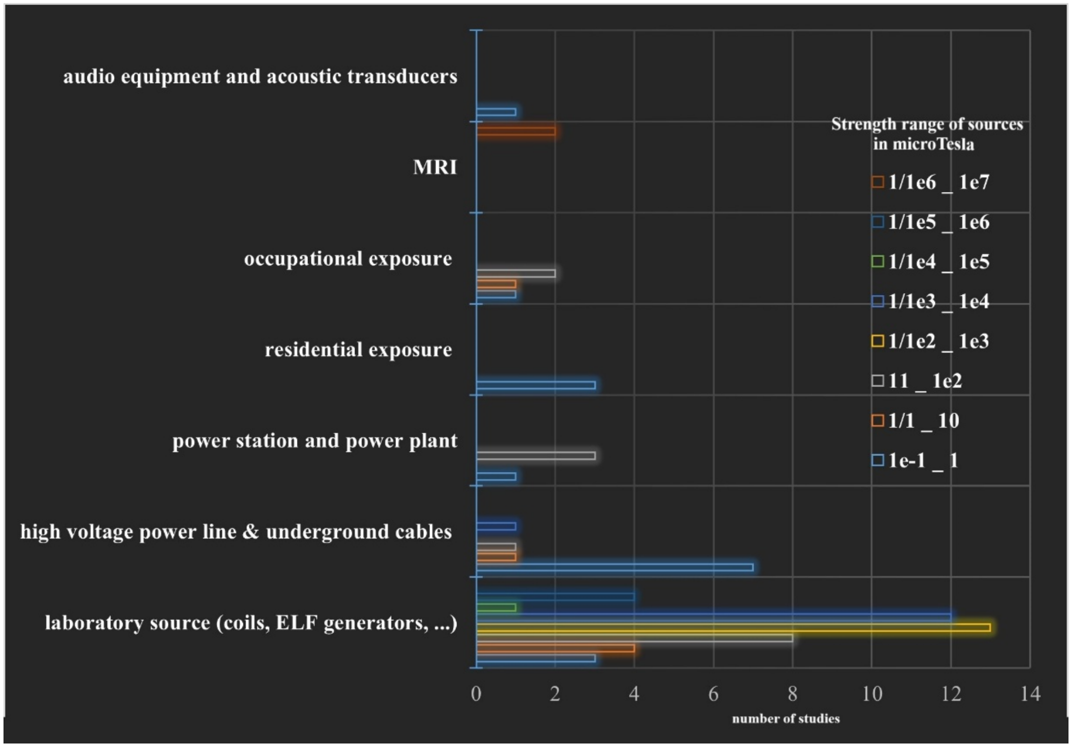

Figure 6. Distribution of ELF-EMF Sources and the Number of Studies across Different Magnetic Field Strengths (Measured in MicroTesla, µT)

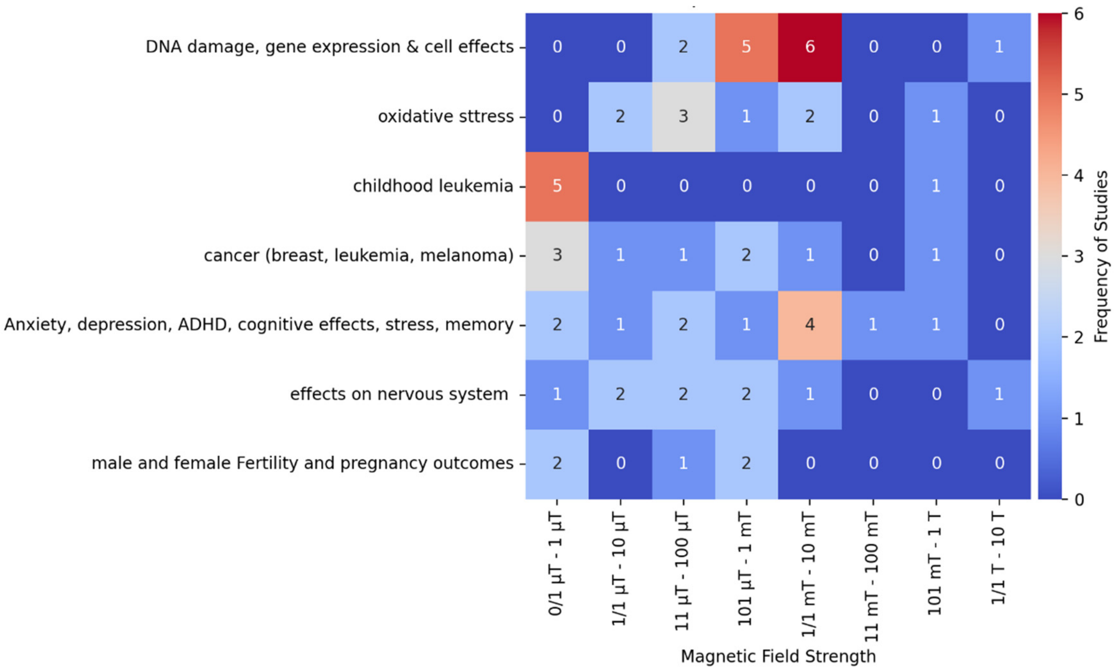

Figure 7. Frequency of Studies on Adverse Health Effects of ELF-EMFs across Different Magnetic Field Strengths

fields (ELF-EMFs) has primarily concentrated on their potential health effects, with particular emphasis on DNA damage, leukemia, anxiety, and oxidative stress. The existing body of literature provides critical insights into these areas while also highlighting the need for further exploration of less-studied outcomes. Numerous studies have established a link between ELF-EMF exposure and DNA damage, which can trigger mutations and elevate cancer risk—particularly in cases of childhood leukemia [80]. Mahdavi et al. (2015) demonstrated an association between ELF-EMFs and leukemia, identifying oxidative stress and DNA damage as significant outcomes. They emphasized the need for further research into less-explored areas, such as cardiovascular and endocrine-related effects [81]. These findings underscore the carcinogenic potential of ELF-EMFs and the importance of continued investigation into their genotoxic effects. ELF-EMF exposure has also been associated with anxiety-like behaviors, potentially mediated by oxidative stress and disruptions in neurotransmitter balance [82]. These mechanisms suggest that ELF-EMFs may influence mental health through biochemical and physiological pathways, warranting further studies in this domain [83]. Additionally, evidence suggests that ELF-EMFs can adversely affect cognitive functions and disrupt normal brain activity, contributing to sleep disturbances and other neurological issues [80, 84]. Certain health outcomes including ADHD, apoptosis, and hepatic effects remain underrepresented in the current literature [84]. While considerable attention has been directed toward neurological and genetic effects, the paucity of research on cardiovascular and endocrine-related outcomes underscores the need for a more comprehensive investigation. Expanding the focus to these underexplored areas could provide a more holistic understanding of the potential health impacts of ELF-EMF exposure.

In examining the geographical distribution of studies in the field of ELF-EMF research, distinct regional patterns emerge. In Asia, countries such as Iran and China have made significant contributions, often focusing on residential exposures and their broader public health implications. These studies frequently address potential health risks in densely populated urban areas, emphasizing the need for public awareness and preventive strategies. In contrast, research in the United States and several European nations such as Germany and Denmark has largely concentrated on occupational exposures. These studies typically examine the health risks faced by workers in high-exposure industries, such as power line maintenance and manufacturing. This emphasis on occupational settings reflects a combination of regulatory attention and the elevated exposure levels characteristic of these environments.

Several factors contribute to the concentration of ELF-EMF research activity in North America, Europe, and Asia. For example, epidemiological studies in North America have reported associations between ELF-EMF exposure and increased cancer risk, particularly in the United States. A meta-analysis by Zhang et al. (2015) identified a statistically significant increase in cancer risk among ELF-EMF-exposed populations in North America (OR = 1.10; 95% CI: 1.01–1.20; $P = 0.03$). This finding likely drives sustained research interest in the region. In contrast, studies from Europe have reported no significant association between ELF-EMF exposure and cancer risk, highlighting regional inconsistencies. These discrepancies may act as a catalyst for further research in both regions to clarify the conflicting results [85].

Beyond health risks, the potential therapeutic applications of ELF-EMFs have also garnered increasing attention. Studies have explored their role in regenerative medicine and skin injury treatment, particularly focusing on effects related to cell proliferation, differentiation, and oxidative stress in various cell types. Notable examples include investigations on human keratinocytes and cancer cell lines, which suggest potential benefits of ELF-EMFs in promoting tissue repair and modulating cellular behavior [86].

As illustrated in Figures 4 to 6, experimental studies using laboratory-generated magnetic fields in the range of 10^2–10^3 μT represent the most prevalent research approach in this field. This trend reflects the scientific community's preference for controlled experimental conditions that allow precise manipulation of moderate-intensity magnetic fields. However, some studies extend their investigations to higher field strengths (10^4–10^5 μT), examining the effects of intense exposures on biological systems and materials.

In contrast, research on ELF-EMFs associated with high-voltage power lines and underground cables primarily targets lower field strengths (0.1–10 μT), which represent the real-world exposure levels typically experienced near such infrastructures. For instance, field intensities measured around medium-voltage network equipment remain significantly below established safety thresholds; however, concerns about prolonged exposure have prompted investigations into potential long-term health risks [87]. These studies align with public exposure standards and underscore the importance of continued environmental monitoring to ensure regulatory compliance and public health protection.

High-intensity fields are often explored in experimental settings to assess their safety implications for both materials and biological systems. For instance, studies on electric field intensities around 500 kV transmission lines evaluate compliance with safety standards, while investigating configuration strategies to minimize exposure, such as optimizing conductor design (88). Additionally, modeling and simulation studies provide valuable insights into field behavior and mitigation strategies, such as using phase splitting to reduce electric field intensity and power loss in conductors [89].

Residential exposure studies typically examine field strengths in the 0.1−1 μT range, indicating that ELF-EMF levels in home environments near power sources are generally low. On the other hand, occupational exposure studies exhibit a broader range, with field strengths often concentrated between 1−100 μT. This variation highlights the diverse exposure risks present in workplace settings compared to residential areas, and underscores the importance of investigating the potential long-term health impacts of occupational exposure. MRI studies represent a distinct category, characterized by extremely high field strengths (10^6−10^7 μT), consistent with the powerful magnetic fields required for medical imaging applications. These studies are critical for ensuring the safety of both patients and healthcare workers exposed to such intense fields.

Overall, the findings demonstrate a strong focus on controlled laboratory research, particularly under moderate- to high-intensity conditions. While these studies provide valuable insights into the mechanisms of ELF-EMF interactions, they also highlight a gap in real-world, long-term research addressing chronic effects in occupational and residential settings. Bridging this gap is essential for developing a more comprehensive understanding of ELF-EMF exposure and its potential health implications.

CONCLUSION

This review highlights the complex and multifaceted relationship between exposure to extremely low-frequency electromagnetic fields (ELF-EMFs) and human health. A diverse range of studies has investigated the potential adverse effects, spanning neurological, oncological, genetic, and mental health outcomes. While strong evidence supports associations with specific conditions such as childhood leukemia, DNA damage, and oxidative stress, findings remain inconsistent for other health effects, including anxiety, depression, and cognitive impairments. These discrepancies underscore the challenges of establishing definitive causal relationships due to methodological limitations, including exposure misclassification, confounding variables, and variability in study designs. Geographically, research activity is concentrated in North America, Europe, and Asia, with distinct focuses on residential and occupational exposures. Laboratory-based experimental studies dominate the field, providing valuable mechanistic insights under controlled conditions. However, real-world exposures in residential and occupational settings remain underexplored, particularly at low to moderate field strengths. This gap highlights the need for comprehensive, long-term epidemiological research to assess chronic effects in everyday environments.

Future research should prioritize underrepresented areas, such as cardiovascular, endocrine, and hepatic outcomes, while also addressing regional disparities in study focus. Policymakers and public health officials must collaborate to refine exposure guidelines and enhance public awareness of potential risks. By bridging existing research gaps and refining study methodologies, the scientific community can provide more definitive conclusions to guide public health strategies.

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