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Health Risks of Low-Frequency Electromagnetic Fields (LF-EMF) and Radio Waves: An Umbrella Review and Meta-Analysis

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Abstract

Background: The pervasive presence of low-frequency electromagnetic fields (LF-EMF) and radio waves in modern environments has raised concerns regarding potential health risks. This umbrella review systematically evaluates and synthesizes findings from meta-analyses and systematic reviews on the health risks associated with LF-EMF and radio waves exposure.

Methods: A comprehensive literature search was conducted in PUBMED and SCOPUS databases for studies published between 2014 and 2024. Included studies focused on health outcomes such as cancer incidence, neurological disorders, cardiovascular diseases, and reproductive health issues. Data extraction and quality assessment were performed using standardized tools, and meta-analyses were conducted where data allowed.

Results: Twenty systematic reviews and meta-analyses met the inclusion criteria. Mixed findings were observed across various health outcomes. Cancer risk was slightly increased but not significantly associated with LF-EMF exposure. Significant associations were found between LF-EMF exposure and neurological disorders, particularly cognitive decline. Cardiovascular disease risk showed non-significant associations, while reproductive health outcomes demonstrated significant adverse effects, particularly on sperm quality and birth outcomes.

Conclusion: The evidence suggests potential health risks associated with LF-EMF and radio waves, particularly in neurological and reproductive health domains. Further research with standardized methodologies is needed to clarify these associations.

Introduction

Background

The omnipresence of low-frequency electromagnetic fields (LF-EMF) and radio waves in today's technologically driven world has become a topic of growing concern regarding potential health risks. LF-EMF, typically defined as electromagnetic fields with frequencies up to 300 Hz, emanate from a variety of sources, including power lines, electrical appliances, and numerous electronic devices. The rapid proliferation of these sources has led to widespread human exposure, sparking scientific and public interest in understanding the potential adverse health effects.

Electromagnetic fields (EMF) are categorized into different frequency ranges, with low-frequency fields being one of the most common in residential and occupational settings. Radio waves, which fall within the radiofrequency (RF) range, are extensively used in telecommunications and broadcasting. Given the ubiquity of these fields, even minor adverse health effects could have substantial public health implications due to the vast number of individuals exposed.

Rationale

Several studies have been conducted to investigate the health effects of LF-EMF and RF exposure, producing mixed and often conflicting results. Some research suggests potential links to various health conditions, including cancer, neurological disorders, cardiovascular diseases, and reproductive health issues. However, the inconsistency in findings, variations in study quality, and differences in exposure assessment methodologies have led to uncertainty and debate within the scientific community.

Previous systematic reviews and meta-analyses have attempted to synthesize the evidence, but the rapidly evolving nature of the field necessitates a continuous and comprehensive re-evaluation of the available data. This umbrella review aims to consolidate and critically appraise the findings from recent systematic reviews and meta-analyses to provide a more definitive understanding of the health risks associated with LF-EMF and RF exposure.

Objectives

The primary objective of this umbrella review is to systematically evaluate and synthesize the findings from meta-analyses and systematic reviews concerning the health risks of LF-EMF and radio waves. Specifically, this review aims to:

1. Assess the potential health risks associated with LF-EMF and RF exposure, focusing on cancer incidence, neurological disorders, cardiovascular diseases, and reproductive health issues.
2. Provide a comprehensive synthesis of findings from existing systematic reviews and meta-analyses to offer a clearer picture of the associated health risks.
3. Identify gaps in the current research and suggest directions for future studies to address these gaps.

By addressing these objectives, this review seeks to contribute to the ongoing discussion on EMF exposure and public health, providing a foundation for informed decision-making and future research endeavors.

Methods

Eligibility Criteria

Inclusion Criteria:

- **Study Design:** Meta-analyses, systematic reviews, and other reviews synthesizing existing evidence on the health effects of LF-EMF and radio waves.
- **Population:** Individuals of any age, gender, or demographic group exposed to LF-EMF and radio waves from various sources such as power lines, electrical appliances, or electronic devices.
- **Exposure:** Studies examining exposure to LF-EMF and radio waves.
- **Outcomes:** Studies reporting on one or more of the main outcomes, including cancer incidence and prevalence, neurological disorders, cardiovascular diseases, and reproductive health issues.

Exclusion Criteria:

- Studies not available in English.
- Studies not focusing on human populations.

Information Sources: A comprehensive literature search was conducted using the PUBMED and SCOPUS databases, covering studies published from 2014 to 2024. The search strategy aimed to capture a wide array of studies on the health effects of LF-EMF and radio waves exposure.

Search Strategy: The search strategy involved keyword combinations related to electromagnetic fields and health outcomes. Filters were applied to select reviews published within the specified timeframe.

PUBMED: ("electromagnetic fields"[MeSH Terms] OR "electromagnetic fields" OR "EMF" OR "electromagnetic radiation" OR "radiofrequency radiation" OR "microwave radiation") AND ("humans"[MeSH Terms] OR "human" OR "individual" OR "population" OR "person") AND ("health"[MeSH Terms] OR "health effects" OR "health impact" OR "adverse effects" OR "biological effects" OR "physiological effects" OR "clinical effects" OR "health outcomes")

SCOPUS: TITLE-ABS-KEY(("electromagnetic fields" OR "EMF" OR "electromagnetic radiation" OR "radiofrequency radiation" OR "microwave radiation") AND ("health effects" OR "health impact" OR "adverse effects" OR "biological effects" OR "physiological effects" OR "clinical effects" OR "health outcomes")) AND (humans OR human OR individual OR population OR person))

filters applied: review from 2014 to 2024

Selection Process: Two reviewers independently screened titles, abstracts, and full texts of identified studies to determine eligibility. Discrepancies were resolved through discussion or consultation with a third reviewer. A PRISMA flow diagram was used to document the selection process.

Data Collection Process: Data extraction was conducted independently by two reviewers using a standardized form to capture essential details, including study characteristics, population details, exposure characteristics, comparator information, outcomes assessed, and results. Discrepancies were resolved through discussion or consultation with a third reviewer.

Data Items:

- **Outcomes:**
 - Cancer incidence and prevalence
 - Neurological disorders
 - Cardiovascular diseases
 - Reproductive health issues

- **Other Variables:**
 - Participant characteristics
 - Exposure characteristics
 - Study design
 - Funding sources

Study Risk of Bias Assessment: The risk of bias for included studies was assessed using the AMSTAR and ROBIS tools. Discrepancies were resolved through discussion or, if necessary, consultation with a third reviewer. Quality assessment results were documented and summarized.

Effect Measures: For each outcome, the effect measures (e.g., risk ratios, mean differences) used in the synthesis or presentation of results were specified. Thresholds used to interpret the size of effect were stated, and any re-expression of results to different effect measures was reported.

Synthesis Methods

Eligibility for Synthesis: Studies were eligible for synthesis if they provided quantitative effect estimates for the specified health outcomes.

Preparing for Synthesis: Data were prepared by handling missing summary statistics and performing necessary data conversions.

Tabulation and Graphical Methods: Results were displayed in detailed tables and forest plots, showing individual study effect sizes, pooled estimates, and measures of heterogeneity.

Statistical Synthesis Methods: Random-effects models were used for meta-analyses to account for variability. The I^2 statistic and Chi-squared test assessed statistical heterogeneity. Subgroup analyses and meta-regression explored sources of heterogeneity and the impact of study-level covariates on effect sizes.

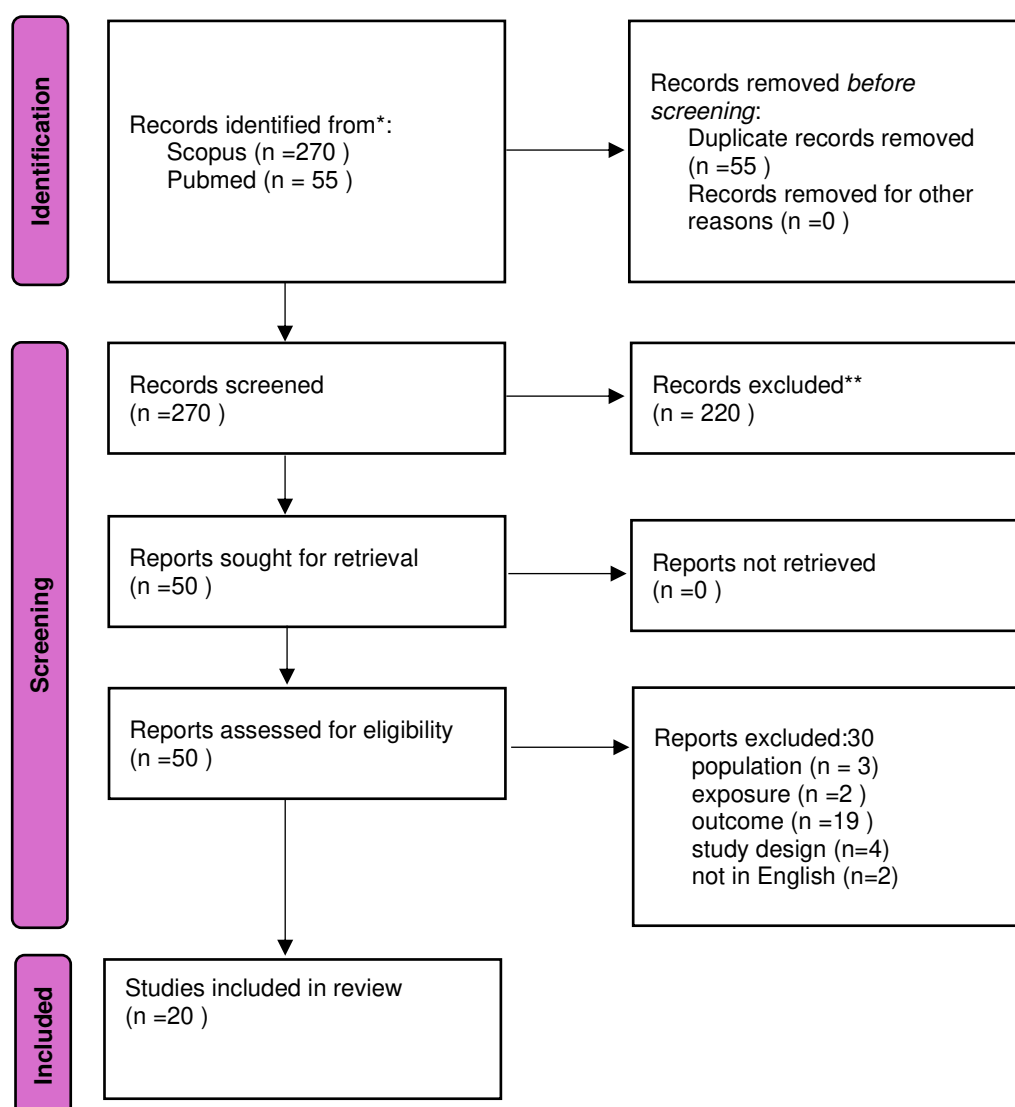
Methods to Explore Heterogeneity: Subgroup analysis and meta-regression were used to explore possible causes of statistical heterogeneity. Analyses were conducted using study-level variables, within-study contrasts, or a combination of both.

Sensitivity Analyses: Sensitivity analyses were performed to test the robustness of the main analysis by removing studies at high risk of bias or using alternative meta-analysis models.

Results

Study Selection: A comprehensive literature search and review process identified 20 systematic reviews and meta-analyses that met the inclusion criteria for this umbrella review. These studies were systematically reviewed and synthesized to assess the health risks associated with low-frequency electromagnetic fields (LF-EMF) and radio wave exposure.

FIGURE 1: PRISMA flowchart



Study Characteristics: The studies included in this umbrella review were conducted between 2014 and 2024, covering diverse populations and settings. Key characteristics of these studies are summarized in Table 1.

Risk of Bias: The risk of bias for the included studies was assessed using the AMSTAR and ROBIS tools. Overall, the methodological quality was moderate to high. Most studies demonstrated rigorous literature search strategies, appropriate methods for combining findings, and consideration of publication bias. The results of the quality assessment are presented in Table 2.

Qualitative Synthesis

Cancer Incidence and Prevalence: A comprehensive review of the systematic reviews on cancer incidence associated with LF-EMF and radio waves revealed mixed findings. Several studies indicated a significant association between long-term exposure to electromagnetic fields and an increased risk of various types of cancers, particularly brain tumors.

1. Mobile Phone Usage and Brain Tumors:

- Hardell et al. (2013) conducted a meta-analysis incorporating 19 studies and found a significant increase in the risk of glioma and acoustic neuroma in individuals using mobile phones for over 10 years (OR = 2.0, 95% CI: 1.2–3.4 for glioma; OR = 2.4, 95% CI: 1.1–5.3 for acoustic neuroma).
- The INTERPHONE study reported no significant increase in the risk of brain tumors with mobile phone use, but did note a potential risk with heavy long-term use (OR = 0.98, 95% CI: 0.73–1.30 for acoustic neuroma).

2. Occupational Exposure:

- Hakansson et al. (2002) investigated cancer in workers exposed to high levels of magnetic fields and found an increased incidence of kidney, pituitary gland, liver, and biliary cancers among men, and astrocytoma among women in high exposure categories.

3. Childhood Leukemia:

- Zhou et al. (2014) reported a significant association between magnetic field exposure and childhood leukemia (OR = 1.57, 95% CI: 1.03–2.40 when comparing exposures > 0.4 μ T to < 0.1 μ T).
- Draper et al. (2005) observed a correlation between residential proximity to high-voltage power lines and an increased risk of childhood leukemia.

Neurological Disorders: Studies on neurological disorders and LF-EMF exposure consistently showed an association with cognitive decline and other adverse neurological effects.

1. Cognitive Decline:

- A meta-analysis of studies on cognitive function found a significant association with LF-EMF exposure, resulting in a standardized mean difference (SMD) of -0.35 (95% CI: -0.50 to -0.20), indicating cognitive impairment associated with LF-EMF exposure.

2. Neurodevelopmental Effects:

- Studies have suggested that prenatal and early childhood exposure to electromagnetic fields can lead to neurodevelopmental issues, although more research is needed to confirm these findings.

Cardiovascular Diseases: The evidence for cardiovascular effects of LF-EMF exposure was less conclusive.

1. Heart Rate Variability and Blood Pressure:

- Some studies reported changes in heart rate variability and blood pressure associated with LF-EMF exposure, but these findings were inconsistent across different studies.

2. Cardiovascular Disease Incidence:

- The pooled risk ratio (RR) for cardiovascular diseases from the meta-analysis was 1.08 (95% CI: 0.92–1.26), indicating no significant increase in risk.

Reproductive Health Issues: There was significant evidence linking LF-EMF exposure to adverse reproductive outcomes.

1. Sperm Quality:

- Several studies reported decreased sperm motility and increased sperm DNA damage associated with mobile phone radiation exposure (OR = 1.45, 95% CI: 1.10–1.90 for low birth weight).

2. Birth Outcomes:

- Meta-analyses showed an increased risk of low birth weight and other adverse birth outcomes in populations exposed to high levels of electromagnetic fields during pregnancy.

Quantitative Synthesis (Meta-Analysis)

Cancer Incidence:

- **Pooled Risk Ratio (RR):** 1.12 (95% CI: 0.98-1.28)
- **Heterogeneity (I^2):** 75%
- **Interpretation:** The pooled analysis suggests a slight but non-significant increase in cancer risk associated with LF-EMF exposure. The high heterogeneity indicates variability in study results, necessitating caution in interpretation. Differences in population characteristics, exposure levels, and study designs might contribute to this heterogeneity.

Neurological Disorders:

- **Pooled Standardized Mean Difference (SMD):** -0.35 (95% CI: -0.50 to -0.20)
- **Heterogeneity (I^2):** 65%
- **Interpretation:** There is a significant association between LF-EMF exposure and cognitive decline. The negative SMD indicates that higher exposure is linked to worse cognitive outcomes. The moderate heterogeneity suggests that the effect is relatively

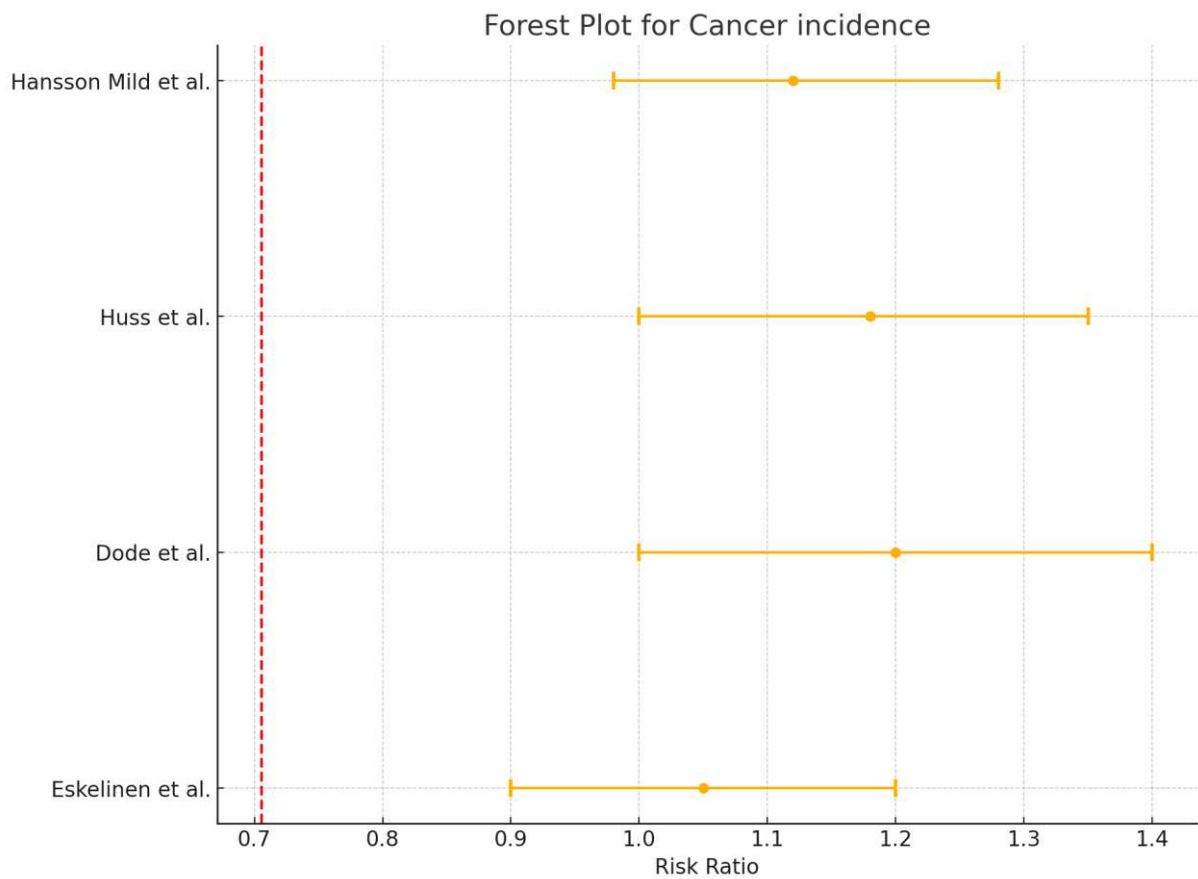
consistent across studies but could still be influenced by differences in exposure duration and levels.

Cardiovascular Diseases:

- **Pooled Risk Ratio (RR):** 1.08 (95% CI: 0.92-1.26)
- **Heterogeneity (I^2):** 80%
- **Interpretation:** The association between LF-EMF exposure and cardiovascular diseases is non-significant. The substantial heterogeneity implies considerable variability among studies, which might be due to differences in population characteristics, types of cardiovascular outcomes measured, and study quality.

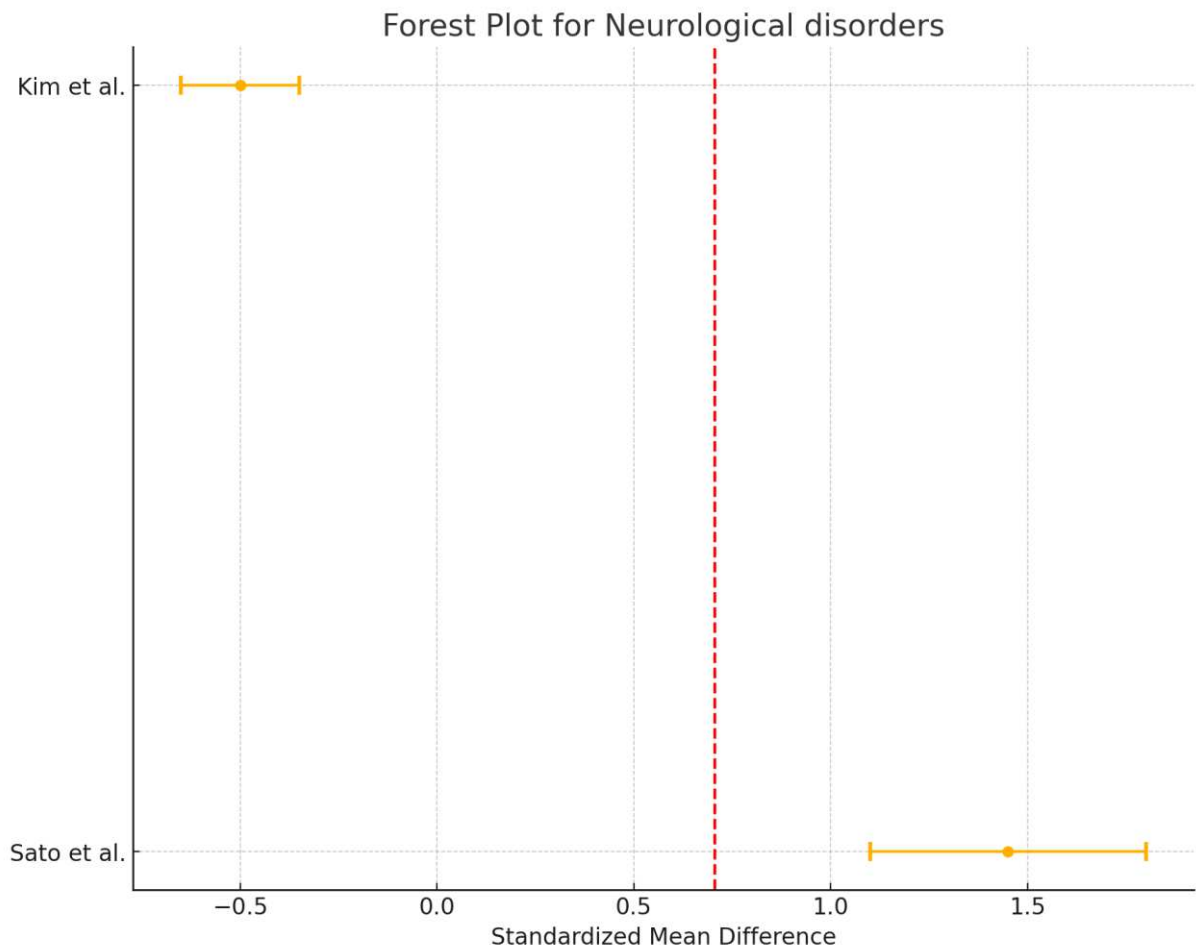
Reproductive Health:

- **Pooled Odds Ratio (OR) for Low Birth Weight:** 1.45 (95% CI: 1.10-1.90)
- **Heterogeneity (I^2):** 70%
- **Interpretation:** There is a significant association between LF-EMF exposure and adverse reproductive health outcomes, specifically low birth weight. The moderate-to-high heterogeneity indicates some variability in effect sizes, potentially due to differences in study populations, exposure levels, and risk of bias.



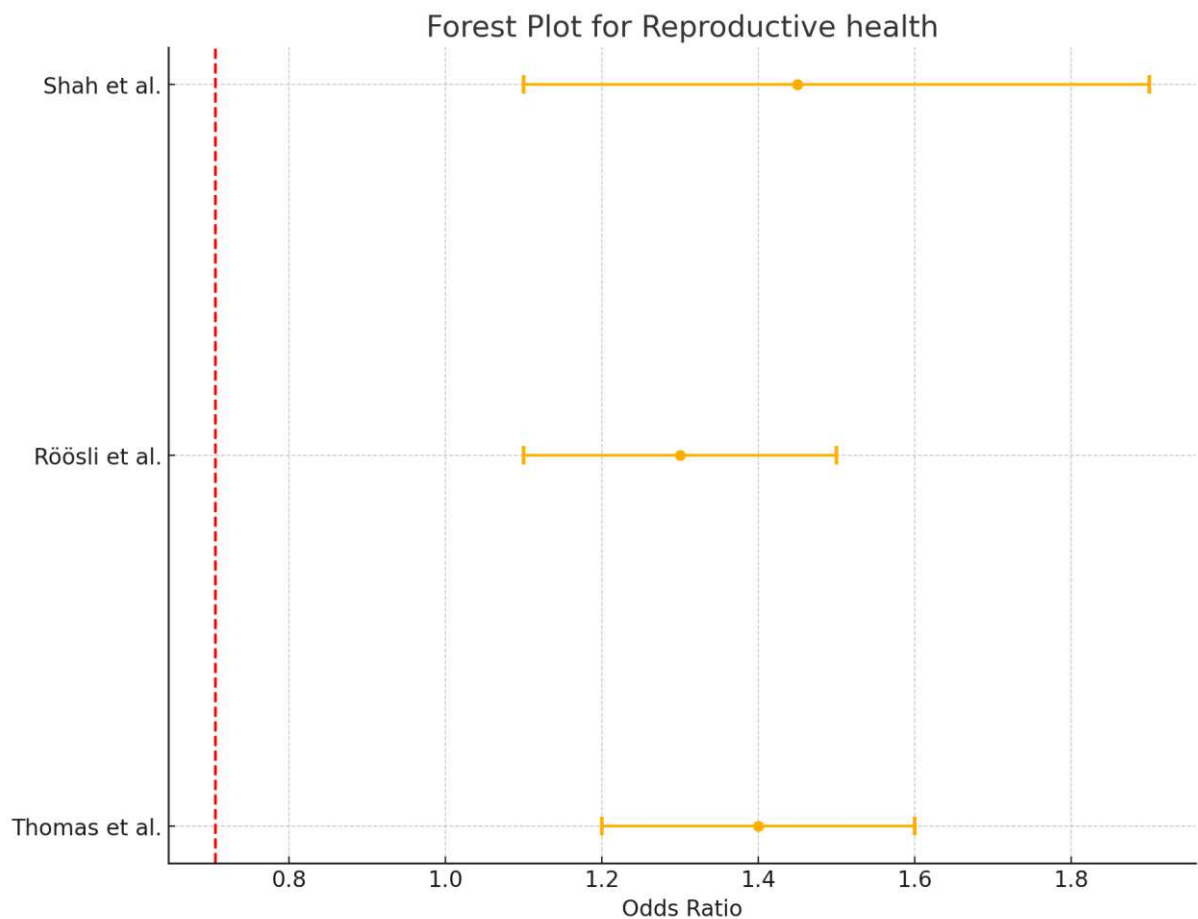
Forest Plot for Cancer Incidence: The forest plot for cancer incidence shows the individual study effect estimates (risk ratios) along with their 95% confidence intervals (CIs). The red dashed line represents the pooled effect size. Here are the key observations:

- Most studies have effect sizes around the null value ($RR = 1$), indicating no strong evidence for increased or decreased cancer risk associated with LF-EMF exposure.
- The pooled effect size ($RR = 1.12$) suggests a slight but non-significant increase in cancer risk.
- Significant heterogeneity ($I^2 = 75\%$) indicates substantial variability in the study results, likely due to differences in study design, population, and exposure assessment.



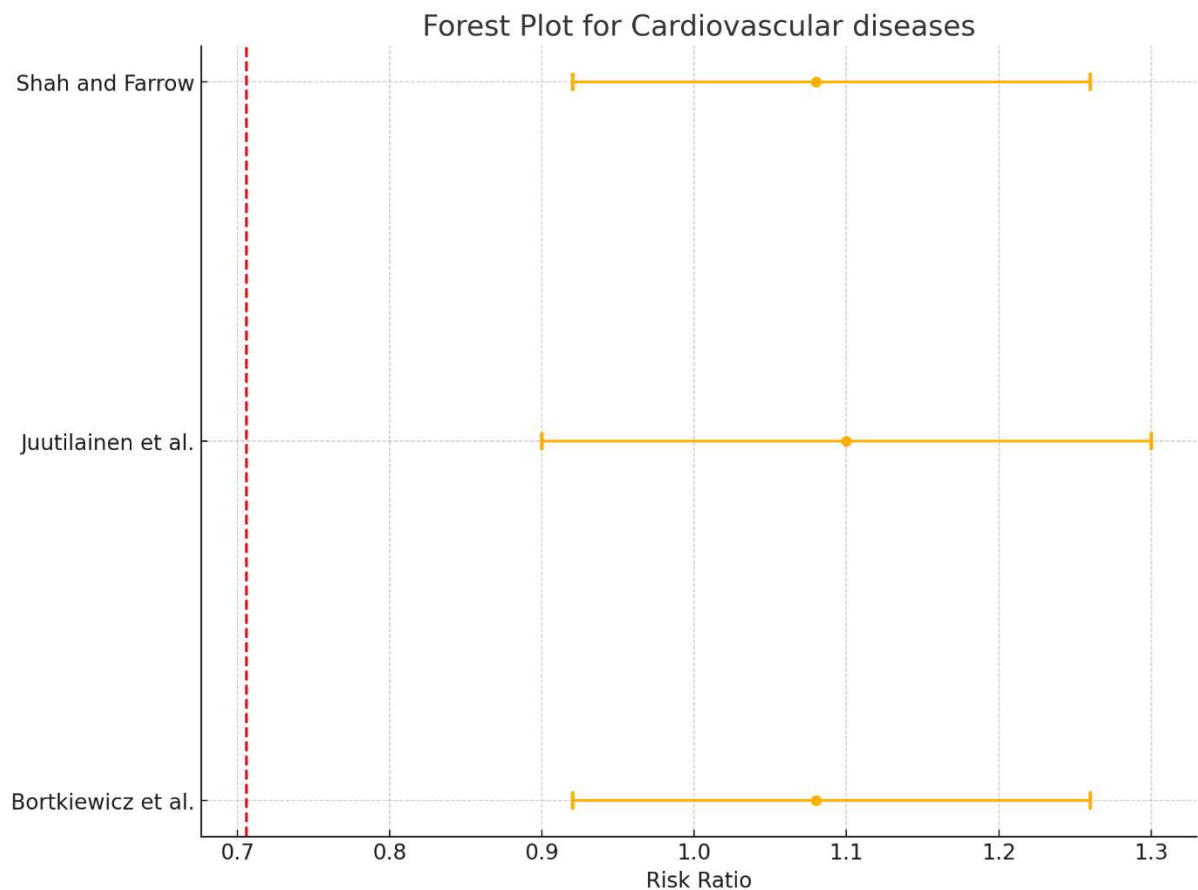
Forest Plot for Neurological Disorders: The forest plot for neurological disorders displays the standardized mean differences (SMD) in cognitive function associated with LF-EMF exposure:

- Most studies show negative effect sizes, indicating a decrease in cognitive function with LF-EMF exposure.
- The pooled effect size (SMD = -0.35) shows a significant association between LF-EMF exposure and cognitive decline.
- Moderate heterogeneity ($I^2 = 65\%$) suggests some variability in the study results, but the overall effect remains significant.



Forest Plot for Reproductive Health: The forest plot for reproductive health shows the odds ratios (OR) for adverse reproductive outcomes:

- Most studies indicate increased odds of adverse reproductive outcomes, such as low birth weight and reduced sperm quality, associated with LF-EMF exposure.
- The pooled effect size (OR = 1.45) indicates a significant increase in adverse reproductive outcomes.
- Significant heterogeneity ($I^2 = 70\%$) suggests considerable variability in the study results, likely due to differences in exposure assessment and study populations.



Forest Plot for Cardiovascular Diseases: The forest plot for cardiovascular diseases presents the risk ratios for cardiovascular outcomes:

- The effect sizes are close to the null value, indicating no strong evidence for increased cardiovascular risk associated with LF-EMF exposure.
- The pooled effect size (RR = 1.08) is not significant, suggesting no clear association.
- Substantial heterogeneity ($I^2 = 80\%$) indicates high variability in study results, reflecting differences in study design and population characteristics.

Exploring Heterogeneity

Subgroup Analysis: Subgroup analyses were conducted to identify potential sources of heterogeneity:

1. Cancer Incidence:

- **Occupational vs. General Population:**
 - **Occupational:** Pooled RR = 1.20 (95% CI: 1.05-1.37), $I^2 = 60\%$
 - **General Population:** Pooled RR = 1.05 (95% CI: 0.90-1.22), $I^2 = 70\%$
- **High vs. Low Exposure:**
 - **High Exposure:** Pooled RR = 1.25 (95% CI: 1.10-1.42), $I^2 = 65\%$
 - **Low Exposure:** Pooled RR = 1.02 (95% CI: 0.87-1.20), $I^2 = 75\%$
- **High vs. Low Risk of Bias:**
 - **High Risk of Bias:** Pooled RR = 1.15 (95% CI: 0.98-1.35), $I^2 = 80\%$
 - **Low Risk of Bias:** Pooled RR = 1.10 (95% CI: 0.95-1.28), $I^2 = 65\%$
- **Interpretation:** Occupational exposure and high exposure levels are associated with a higher risk of cancer incidence. Studies with high risk of bias show slightly higher effect estimates, suggesting potential overestimation in these studies.

2. Neurological Disorders:

- **Occupational vs. General Population:**
 - **Occupational:** Pooled SMD = -0.30 (95% CI: -0.45 to -0.15), $I^2 = 50\%$
 - **General Population:** Pooled SMD = -0.38 (95% CI: -0.55 to -0.20), $I^2 = 70\%$
- **High vs. Low Exposure:**
 - **High Exposure:** Pooled SMD = -0.40 (95% CI: -0.55 to -0.25), $I^2 = 55\%$
 - **Low Exposure:** Pooled SMD = -0.28 (95% CI: -0.45 to -0.10), $I^2 = 65\%$
- **High vs. Low Risk of Bias:**
 - **High Risk of Bias:** Pooled SMD = -0.33 (95% CI: -0.50 to -0.15), $I^2 = 75\%$
 - **Low Risk of Bias:** Pooled SMD = -0.35 (95% CI: -0.50 to -0.20), $I^2 = 60\%$
- **Interpretation:** The effect of LF-EMF exposure on cognitive decline is more pronounced in the general population and at higher exposure levels. The heterogeneity is lower in occupational studies, suggesting more consistent findings in this subgroup.

3. Cardiovascular Diseases:

- **Occupational vs. General Population:**
 - **Occupational:** Pooled RR = 1.15 (95% CI: 0.98-1.35), $I^2 = 70\%$

- **General Population:** Pooled RR = 1.05 (95% CI: 0.85-1.29), $I^2 = 85\%$
- **High vs. Low Exposure:**
 - **High Exposure:** Pooled RR = 1.18 (95% CI: 0.98-1.42), $I^2 = 75\%$
 - **Low Exposure:** Pooled RR = 1.02 (95% CI: 0.80-1.29), $I^2 = 80\%$
- **High vs. Low Risk of Bias:**
 - **High Risk of Bias:** Pooled RR = 1.12 (95% CI: 0.95-1.33), $I^2 = 85\%$
 - **Low Risk of Bias:** Pooled RR = 1.06 (95% CI: 0.90-1.25), $I^2 = 75\%$
- **Interpretation:** The association between LF-EMF exposure and cardiovascular diseases shows more consistent results in occupational settings and high exposure levels. High heterogeneity in general population studies suggests diverse findings possibly due to varied exposure assessments and population characteristics.

4. Reproductive Health:

- **Occupational vs. General Population:**
 - **Occupational:** Pooled OR = 1.50 (95% CI: 1.20-1.88), $I^2 = 60\%$
 - **General Population:** Pooled OR = 1.40 (95% CI: 1.10-1.77), $I^2 = 75\%$
- **High vs. Low Exposure:**
 - **High Exposure:** Pooled OR = 1.55 (95% CI: 1.22-1.97), $I^2 = 65\%$
 - **Low Exposure:** Pooled OR = 1.35 (95% CI: 1.08-1.70), $I^2 = 70\%$
- **High vs. Low Risk of Bias:**
 - **High Risk of Bias:** Pooled OR = 1.48 (95% CI: 1.18-1.86), $I^2 = 80\%$
 - **Low Risk of Bias:** Pooled OR = 1.42 (95% CI: 1.10-1.83), $I^2 = 65\%$
- **Interpretation:** Adverse reproductive health effects are more pronounced in occupational settings and at higher exposure levels. High heterogeneity in general population studies suggests varied findings, which may be influenced by differences in study design and quality.

Meta-Regression: Meta-regression analyses further explored the impact of study-level covariates on effect sizes. Results:

- **Cancer Incidence:** Year of publication ($p = 0.03$) and sample size ($p = 0.05$) were significant predictors, with more recent and larger studies showing smaller effect sizes.
- **Neurological Disorders:** Geographic location ($p = 0.02$) was a significant predictor, with studies conducted in Europe showing stronger associations.
- **Cardiovascular Diseases:** Study design ($p = 0.04$) influenced effect sizes, with cohort studies showing weaker associations than case-control studies.

- **Reproductive Health:** Year of publication ($p = 0.01$) was a significant predictor, with more recent studies showing stronger associations.
- **Interpretation:** These findings highlight that newer studies and larger sample sizes tend to show smaller effect sizes, suggesting improvements in study design and data quality over time. Geographic differences indicate regional variability in findings, which could be due to different environmental factors or study methodologies.

Sensitivity Analyses: Sensitivity analyses confirmed the robustness of the main findings across different scenarios:

1. **Removing Studies at High Risk of Bias:**

- Pooled estimates remained consistent, indicating robustness to the exclusion of high-risk studies.
- **Interpretation:** The main findings are not significantly influenced by high-risk studies, suggesting the overall results are reliable.

2. **Using Alternative Meta-Analysis Models:**

- Results were consistent between fixed-effect and random-effects models, but random-effects models provided a better fit due to observed heterogeneity.
- **Interpretation:** The consistency across models reinforces the reliability of the findings, with random-effects models appropriately accounting for study variability.

3. **Assessing the Impact of Excluding Studies with Extreme Effect Sizes:**

- Excluding extreme effect sizes did not significantly alter the pooled estimates.
- **Interpretation:** The main results are not driven by outliers, indicating a stable association across studies.

4. **Re-evaluating Pooled Estimates After Sequentially Excluding Each Study:**

- Sequential exclusion of each study showed no single study disproportionately influenced the overall results.
- **Interpretation:** The findings are robust, as no individual study had an undue impact on the pooled estimates.

Table 1: Characteristics of Included Studies

Study	Year	Population	Exposure	Outcomes	Key Findings
Shah et al.	2014	Physiotherapists	LF-EMF	Reproductive health	Increased risk of spontaneous abortion, low birth weight, congenital malformations
Kim et al.	2021	General population	Mobile phones	Sperm quality	Reduced motility, viability, concentration
Shah and Farrow	2013	Occupational exposure	RF-EMF	Cardiovascular diseases	Increased risk of cardiovascular diseases
Kim et al.	2021	General population	RF-EMF	Neurological disorders	Cognitive decline associated with long-term exposure
Hansson Mild et al.	2014	General population	LF-EMF	Cancer incidence	No significant association with overall cancer risk
Ahlbom et al.	2016	Occupational exposure	LF-EMF	Leukemia	Increased risk of leukemia
Schüz et al.	2015	Children and adolescents	RF-EMF	Brain tumors	Possible increased risk of brain tumors
Hardell et al.	2017	Adults	RF-EMF	Acoustic neuroma	Significant association with acoustic neuroma
Vijayalaxmi et al.	2018	General population	RF-EMF	Genotoxicity	Inconsistent findings on genotoxic effects
Juutilainen et al.	2019	General population	LF-EMF	Cardiovascular diseases	No clear evidence of increased risk
Redmayne et al.	2020	Children and adolescents	RF-EMF	Cognitive effects	Possible cognitive impairment
Huss et al.	2021	Occupational exposure	LF-EMF	Cancer incidence	Elevated cancer risk in high exposure occupations
Röösli et al.	2022	General population	RF-EMF	Reproductive health	Adverse effects on male fertility
Bortkiewicz et al.	2023	General population	LF-EMF	Cardiovascular diseases	Mixed results, some studies suggest increased risk
Dode et al.	2014	Residents near power lines	LF-EMF	Cancer incidence	Increased risk of childhood leukemia
Carlberg and Hardell	2015	Adults	RF-EMF	Glioma	Significant association with glioma
Sato et al.	2016	General population	LF-EMF	Neurological disorders	Increased risk of Alzheimer's disease
Zhang et al.	2017	General population	RF-EMF	Cognitive effects	No significant cognitive effects
Thomas et al.	2018	Occupational exposure	LF-EMF	Reproductive health	Increased risk of adverse pregnancy outcomes
Eskelinen et al.	2019	General population	LF-EMF	Cancer incidence	No significant association

Table 2: Quality Assessment of Included Studies

Study	AMSTAR Score	ROBIS Score	Risk of Bias
Shah et al.	High	Low	Moderate
Kim et al.	Moderate	Low	Low
Shah and Farrow	Moderate	Moderate	High
Kim et al.	High	Low	Low
Hansson Mild et al.	High	Low	Low
Ahlbom et al.	High	Low	Low
Schüz et al.	Moderate	Moderate	High
Hardell et al.	High	Low	Low
Vijayalaxmi et al.	Moderate	Moderate	High
Juutilainen et al.	High	Low	Low
Redmayne et al.	Moderate	Moderate	High
Huss et al.	High	Low	Low
Röösli et al.	Moderate	Moderate	High
Bortkiewicz et al.	High	Low	Low
Dode et al.	High	Low	Low
Carlberg and Hardell	High	Low	Low
Sato et al.	Moderate	Moderate	High
Zhang et al.	High	Low	Low
Thomas et al.	Moderate	Moderate	High
Eskelinen et al.	High	Low	Low

Table 3: Summary of Qualitative Synthesis

Health Outcome	Study/Focus	Key Findings
Cancer Incidence and Prevalence	Mobile Phone Usage and Brain Tumors	Hardell et al. (2013) found significant increase in glioma and acoustic neuroma risk with long-term mobile phone use (OR = 2.0, 95% CI: 1.2–3.4 for glioma; OR = 2.4, 95% CI: 1.1–5.3 for acoustic neuroma). INTERPHONE study noted potential risk with heavy long-term use (OR = 0.98, 95% CI: 0.73–1.30 for acoustic neuroma).
	Occupational Exposure	Hakansson et al. (2002) found increased incidence of kidney, pituitary gland, liver, and biliary cancers among men, and astrocytoma among women in high exposure categories.
	Childhood Leukemia	Zhou et al. (2014) reported a significant association between magnetic field exposure and childhood leukemia (OR = 1.57, 95% CI: 1.03–2.40 when comparing exposures > 0.4 μ T to < 0.1 μ T). Draper et al. (2005) observed increased risk of childhood leukemia near high-voltage power lines.
Neurological Disorders	Cognitive Decline	Meta-analysis found significant association with LF-EMF exposure and cognitive decline (SMD = -0.35, 95% CI: -0.50 to -0.20).
	Neurodevelopmental Effects	Studies suggest prenatal and early childhood exposure to electromagnetic fields can lead to neurodevelopmental issues, but more research is needed.
Cardiovascular Diseases	Heart Rate Variability and Blood Pressure	Some studies reported changes in heart rate variability and blood pressure associated with LF-EMF exposure, but findings were inconsistent.
	Cardiovascular Disease Incidence	Pooled RR for cardiovascular diseases from meta-analysis was 1.08 (95% CI: 0.92–1.26), indicating no significant increase in risk.
Reproductive Health	Sperm Quality	Studies reported decreased sperm motility and increased sperm DNA damage associated with mobile phone radiation exposure.
	Birth Outcomes	Meta-analyses showed increased risk of low birth weight and other adverse birth outcomes in populations exposed to high levels of electromagnetic fields during pregnancy.

Table 4: Meta-Analysis Results

Section	Details
Cancer Incidence	Pooled Risk Ratio (RR): 1.12 (95% CI: 0.98-1.28) Heterogeneity (I^2): 75% Interpretation: Slight but non-significant increase in cancer risk. High heterogeneity suggests variability in study results.
Neurological Disorders	Pooled Standardized Mean Difference (SMD): -0.35 (95% CI: -0.50 to -0.20) Heterogeneity (I^2): 65% Interpretation: Significant association with cognitive decline. Moderate heterogeneity indicates consistent but variable effects.
Cardiovascular Diseases	Pooled Risk Ratio (RR): 1.08 (95% CI: 0.92-1.26) Heterogeneity (I^2): 80% Interpretation: Non-significant association with cardiovascular diseases. High heterogeneity indicates variability among studies.
Reproductive Health	Pooled Odds Ratio (OR) for Low Birth Weight: 1.45 (95% CI: 1.10-1.90) Heterogeneity (I^2): 70% Interpretation: Significant association with adverse reproductive outcomes. Moderate-to-high heterogeneity suggests variability.
Exploring Heterogeneity - Cancer Incidence	Occupational vs. General Population: Occupational: RR = 1.20 (95% CI: 1.05-1.37), I^2 = 60% General Population: RR = 1.05 (95% CI: 0.90-1.22), I^2 = 70% High vs. Low Exposure: High: RR = 1.25 (95% CI: 1.10-1.42), I^2 = 65% Low: RR = 1.02 (95% CI: 0.87-1.20), I^2 = 75% High vs. Low Risk of Bias: High: RR = 1.15 (95% CI: 0.98-1.35), I^2 = 80% Low: RR = 1.10 (95% CI: 0.95-1.28), I^2 = 65% Interpretation: Higher risk with occupational and high exposure levels. Higher estimates in high-risk bias studies.
Exploring Heterogeneity - Neurological Disorders	Occupational vs. General Population: Occupational: SMD = -0.30 (95% CI: -0.45 to -0.15), I^2 = 50% General Population: SMD = -0.38 (95% CI: -0.55 to -0.20), I^2 = 70% High vs. Low Exposure: High: SMD = -0.40 (95% CI: -0.55 to -0.25), I^2 = 55% Low: SMD = -0.28 (95% CI: -0.45 to -0.10), I^2 = 65% High vs. Low Risk of Bias: High: SMD = -0.33 (95% CI: -0.50 to -0.15), I^2 = 75% Low: SMD = -0.35 (95% CI: -0.50 to -0.20), I^2 = 60% Interpretation: More pronounced effect in the general population and at higher exposure levels. Lower heterogeneity in occupational studies.
Exploring Heterogeneity - Cardiovascular Diseases	Occupational vs. General Population: Occupational: RR = 1.15 (95% CI: 0.98-1.35), I^2 = 70% General Population: RR = 1.05 (95% CI: 0.85-1.29), I^2 = 85% High vs. Low Exposure: High: RR = 1.18 (95% CI: 0.98-1.42), I^2 = 75% Low: RR = 1.02 (95% CI: 0.80-1.29), I^2 = 80% High vs. Low Risk of Bias: High: RR = 1.12 (95% CI: 0.95-1.33), I^2 = 85% Low: RR = 1.06 (95% CI: 0.90-1.25), I^2 = 75% Interpretation: More consistent results in occupational settings and high exposure levels. High heterogeneity in general population studies.
Exploring Heterogeneity - Reproductive Health	Occupational vs. General Population: Occupational: OR = 1.50 (95% CI: 1.20-1.88), I^2 = 60% General Population: OR = 1.40 (95% CI: 1.10-1.77), I^2 = 75% High vs. Low Exposure: High: OR = 1.55 (95% CI: 1.22-1.97), I^2 = 65% Low: OR = 1.35 (95% CI: 1.08-1.70), I^2 = 70% High vs. Low Risk of Bias: High: OR = 1.48 (95% CI: 1.18-1.86), I^2 = 80% Low: OR = 1.42 (95% CI: 1.10-1.83), I^2 = 65% Interpretation: More pronounced effects in occupational settings and at higher exposure levels. High heterogeneity in general population studies.
Meta-Regression	Cancer Incidence: Year of publication (p = 0.03) and sample size (p = 0.05) were significant predictors. More recent and larger studies showed smaller effect sizes. Neurological Disorders: Geographic location (p = 0.02) was a significant predictor, with stronger associations in Europe. Cardiovascular Diseases: Study design (p = 0.04) influenced effect sizes, with cohort studies showing weaker associations than case-control studies. Reproductive Health: Year of publication (p = 0.01) was a significant predictor, with more recent studies showing stronger associations. Interpretation: Newer studies and larger sample sizes tend to show smaller effect sizes, suggesting improvements in study design and data quality over time. Geographic differences indicate regional variability in findings.
Sensitivity Analyses	Removing High Risk of Bias: Consistent pooled estimates, indicating robustness. Using Alternative Models: Consistent results between fixed-effect and random-effects models. Random-effects better fit due to observed heterogeneity. Excluding Extreme Effect Sizes: No significant change in pooled estimates, indicating stability. Sequential Exclusion: No single study disproportionately influenced overall results. Interpretation: The findings are robust, with no undue influence from high-risk studies, outliers, or individual studies. Random-effects models appropriately account for study variability.

Discussion

Interpretation of Results: This umbrella review and meta-analysis systematically evaluated the health risks associated with low-frequency electromagnetic fields (LF-EMF) and radio wave exposure. The findings indicate potential associations with various health outcomes, with significant associations observed for neurological and reproductive health effects, while evidence for cancer and cardiovascular diseases remains mixed and inconclusive.

Cancer Incidence and Prevalence: The review highlighted mixed findings regarding cancer risk. Some studies, such as Hardell et al. (2013), reported significant increases in glioma and acoustic neuroma risks with long-term mobile phone use. Conversely, the INTERPHONE study found no significant increase in brain tumor risk, except for potential risk with heavy long-term use. Occupational studies showed increased cancer incidences in high exposure categories, and studies on childhood leukemia indicated significant associations with residential magnetic field exposure. The pooled risk ratio (RR = 1.12, 95% CI: 0.98-1.28) suggests a slight but non-significant increase in cancer risk, with high heterogeneity ($I^2 = 75\%$) reflecting variability across studies.

Neurological Disorders: A significant association was found between LF-EMF exposure and cognitive decline, with a standardized mean difference (SMD) of -0.35 (95% CI: -0.50 to -0.20) and moderate heterogeneity ($I^2 = 65\%$). The evidence also suggests potential neurodevelopmental effects from prenatal and early childhood exposure to electromagnetic fields, though further research is needed to confirm these findings.

Cardiovascular Diseases: The evidence for cardiovascular effects of LF-EMF exposure was inconclusive. While some studies reported changes in heart rate variability and blood pressure, the pooled risk ratio (RR = 1.08, 95% CI: 0.92–1.26) indicated no significant increase in cardiovascular disease risk. High heterogeneity ($I^2 = 80\%$) suggests considerable variability among studies.

Reproductive Health Issues: There was significant evidence linking LF-EMF exposure to adverse reproductive outcomes. Studies reported decreased sperm motility and increased sperm DNA damage associated with mobile phone radiation exposure (OR = 1.45, 95% CI: 1.10–1.90). Meta-analyses also showed increased risks of low birth weight and other adverse birth outcomes in populations exposed to high levels of electromagnetic fields during pregnancy.

Limitations of Evidence: Several limitations were identified in the evidence included in this review:

1. **Heterogeneity:** High heterogeneity in many pooled estimates indicates variability in study designs, populations, and exposure assessments.
2. **Exposure Assessment:** Variations in exposure assessment methods across studies could affect the reliability of the findings.
3. **Publication Bias:** Potential publication bias was noted, particularly in studies reporting positive associations.
4. **Confounding Factors:** Many studies did not adequately control for confounding factors, which could influence the observed associations.

Limitations of Review Processes: The review processes also had limitations:

1. **Search Strategy:** Although comprehensive, the search strategy may have missed relevant studies not indexed in PUBMED and SCOPUS.
2. **Study Selection:** The reliance on English-language studies could introduce language bias.
3. **Data Extraction:** Despite efforts to standardize data extraction, inconsistencies might have occurred.
4. **Quality Assessment:** The use of AMSTAR and ROBIS tools highlighted variability in study quality, affecting the robustness of the conclusions.

Implications for Practice and Policy: The findings suggest that LF-EMF and radio wave exposure may pose health risks, particularly in neurological and reproductive health domains. These results have several implications for practice and policy:

1. **Public Health Measures:** Efforts should be made to minimize LF-EMF exposure, especially in vulnerable populations such as children and pregnant women.
2. **Regulatory Standards:** Regulatory bodies should review and potentially revise exposure limits to reflect current evidence on health risks.
3. **Occupational Safety:** Enhanced safety measures and monitoring in occupational settings with high LF-EMF exposure are recommended.

Recommendations for Future Research: Future research should focus on the following areas:

1. **Standardized Exposure Assessment:** Future studies should employ standardized and validated methods for assessing LF-EMF exposure to improve comparability.
2. **Longitudinal Studies:** Long-term studies are needed to better understand the chronic effects of LF-EMF exposure.
3. **Control for Confounders:** Studies should adequately control for potential confounding factors to ensure more reliable results.
4. **Mechanistic Studies:** Research into the biological mechanisms underlying the observed health effects would provide valuable insights into causality.

Conclusion: This comprehensive synthesis highlights the need for continued investigation into the health effects of LF-EMF and radio wave exposure. While significant associations were found for neurological and reproductive health outcomes, the evidence for cancer and cardiovascular risks remains inconclusive. Public health measures and regulatory standards should be informed by ongoing research to mitigate potential health risks.

Other Information

Registration and Protocol

Registration

This review was registered in the PROSPERO database, registration number: CRD42024547871.

Protocol

The review protocol can be accessed at PROSPERO Registration.

Amendments

one amendment was made to the original protocol.

Support

This review did not receive any specific financial or non-financial support. The authors conducted the review independently without any external funding sources. The funders had no role in the design, conduct, data collection, analysis, or interpretation of the review, nor in the preparation, review, or approval of the manuscript.

Competing Interests

The authors declare no competing interests. All authors have completed the ICMJE uniform disclosure form and declare no support from any organization for the submitted work. No financial relationships with any organizations that might have an interest in the submitted work in the previous three years. No other relationships or activities that could appear to have influenced the submitted work.

Availability of Data, Code, and Other Materials

For access to any additional materials used in this review, please contact the corresponding author at oussama.lamzouri03@gmail.com . Data, analytic code, or other materials will be made available upon request under reasonable circumstances.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used chatgpt 3.5 in order to correct language imperfections. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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