Journal of Natural Science Review

Vol.3, No. 4, 2025
https://kujnsr.com
E-ISSN: 3006-7804

Health Effects of Electromagnetic Radiation: A Focus on Radiofrequency (RF) and Microwave Radiation

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ABSTRACT

The growing presence of radiofrequency (RF) and microwave electromagnetic radiation (EMR) in everyday environments—driven by widespread mobile communication systems, Wi-Fi networks, and rapidly expanding 5G infrastructure—has raised increasing public health concerns. While RF/MW radiation is categorized as non-ionizing due to its insufficient energy to ionize atoms or molecules, research indicates that it may still interact with biological systems through non-thermal mechanisms such as electromagnetic coupling, induced currents, and oxidative stress. This paper aims to investigate the potential health effects associated with chronic low-level RF/MW exposure. A critical literature review was conducted using recent peer-reviewed studies and health agency guidelines to evaluate observed biological outcomes and compare them with existing safety standards. The review highlights consistent evidence linking prolonged exposure to sleep disruption, increased oxidative stress, neurobehavioral alterations, and potential reproductive risks. Current exposure limits are largely based on thermal effects and may not sufficiently address sub-threshold, long-term biological interactions. This paper identifies a significant research gap in dosimetric criteria and calls for a reevaluation of public health policies. Future research should focus on longitudinal studies in real-world exposure scenarios and explore specific mechanisms such as ion channel modulation and signal modulation sensitivity. These efforts are essential to develop more protective exposure guidelines for increasingly connected populations.

ARTICLE INFO

Article history:

Received: July 14, 2025
Revised: October 23, 2025
Accepted: November 27, 2025
Published: December 31, 225

Keywords:

Cognitive function; Non-thermal effects; Oxidative stress; Public health; Safety standards

To cite this article: Sadiqi, M. R., & Aziz, N. M. Health Effects of Electromagnetic Radiation: A Focus on Radiofrequency (RF) and Microwave Radiation. *Journal of Natural Science Review, 3* (4), 276-292. *https://doi.org/10.62810/jnsr.v3i4.308*

Link to this article: https://kujnsr.com/JNSR/article/view/308

INTRODUCTION

The ubiquity of radiofrequency (RF) and microwave electromagnetic radiation (EMR) in contemporary environments—stemming from mobile communication systems, wireless networks, and emerging 5G technologies—has led to increased scrutiny of potential biological interactions. (Bushberg et al., 2020) Although RF EMR is classified as non-ionizing due to photon energies insufficient to ionize atoms or molecules, it can still deposit energy in biological tissues through electromagnetic coupling, induced currents, and dielectric losses. (ICNIRP, 2020)

From physics perspective, interaction of RF fields with biological matter is governed by well-defined parameters: frequency, field strength, power density, and specific absorption rate (SAR). These quantities determine the distribution and magnitude of energy transfer to tissues and are critical in evaluating thermal and non-thermal effects. Regulatory frameworks such as IEEE C95.1 and ICNIRP 2020 define exposure limits primarily based on SAR thresholds intended to prevent significant tissue heating, typically not exceeding 2 W/kg averaged over 10 g of tissue. (ICNIRP, 2020)

However, increasing empirical evidence—both epidemiological and experimental—suggests the possibility of non-thermal biological effects under sub-threshold exposures. Proposed mechanisms include modulation-dependent neural responses, altered ion channel activity, and cellular oxidative stress, none of which are directly addressed by current dosimetric criteria (Kositsky et al., 2001).

This review presents a critical analysis of the general health effects of RF and microwave radiation from a physicist's standpoint. Emphasis is placed on the electromagnetic principles, bio-interaction mechanisms, and quantitative modeling of field-tissue interactions. The objective is;

- To assess whether reported biological effects are consistent with the known physics of EM wave propagation, absorption, and modulation, and to identify methodological limitations that obscure causal inference.
- The central question guiding this review is:
- What are the health effects of radiofrequency electromagnetic waves (RF-EMWs) on human health, and what mechanisms underlie these effects?
- How does long-term, low-intensity RF/MW exposure affect sleep architecture and circadian rhythm regulation in vulnerable populations such as children and adolescents?

These questions are explored through an analysis of studies conducted on human subjects, with a particular focus on identifying biological mechanisms and observed health outcomes linked to RF-EMW exposure.

METHODS AND MATERIALS

This review was conducted using a structured literature search approach to identify, analyze, and synthesize existing studies on the health effects of radiofrequency electromagnetic waves (RF-EMWs), with an emphasis on human-focused research. Peer-reviewed articles published between 2015 and 2024 were collected from major academic databases, including Google Scholar, IEEE Xplore, and Scopus.Search terms included combinations of keywords such as "radiofrequency electromagnetic waves," "RF-EMW," "health effects," "biological effects," "human studies," and "mechanisms of interaction." Only peer-reviewed articles published in English were included. Studies focusing on human subjects were prioritized, while animal studies and theoretical papers were excluded unless they provided essential background or mechanistic insights relevant to human health.

After screening titles and abstracts for relevance, full-text reviews were conducted to assess study quality and data consistency. The review included a total of approximately 60 studies, from which 47 of them were selected based on their focus on human subjects and empirical findings on health-related outcomes. Findings were organized into thematic categories including types of exposure, proposed biological mechanisms, and observed health effects.

FINDINGS

This study systematically reviewed empirical data on the biological and health effects of radiofrequency (RF) and microwave (MW) electromagnetic radiation (EMR), with emphasis on sub-thermal, chronic exposures. The analysis revealed four key domains consistently addressed in the literature: sleep and circadian disruption, oxidative stress and cellular response, reproductive and developmental impacts, and neurological and cognitive effects.

Quantitative and qualitative data from selected peer-reviewed studies are summarized in Table 1 and Table 2, while graphical representations are shown in Figures 1 and 2.

Table 1. *Summary of Reviewed Studies Showing Sleep and Neurobehavioral Effects of RF/MW EMR*

Study	Exposure Type	Frequency Range	Main Findings
Arnetz et al. (2007)	GSM mobile phone	900 MHz	Reduced REM sleep, increased brain activity
Danker-Hopfe et al. (2010)	UMTS signal	1.9 GHz	Altered EEG patterns, delayed sleep onset
Zhang et al. (2022)	Wi-Fi exposure	2.4 GHz	Decreased melatonin, insomnia-like symptoms

These studies demonstrate a consistent relationship between RF/MW exposure and disruptions to sleep architecture. Alterations in EEG and circadian hormones, including melatonin suppression, suggest modulation-dependent neurological interference (Arnetz et al., 2007; Danker-Hopfe et al., 2010; Zhang et al., 2022).

Table 2. *Oxidative Stress Markers in Animal and Cell Studies Following RF/MW Exposure*

Study	Biological Model	Frequency	ROS/Antioxidant Effect
Yakymenko et al. (2016)	Rat tissue	1800 MHz	Elevated ROS, DNA damage
Kesari et al. (2011)	Rat brain	900 MHz	Decreased glutathione, increased MDA
Lu et al. (2020)	Human fibroblasts	2.45 GHz	Increased oxidative markers, apoptosis

Oxidative stress emerged as a dominant non-thermal effect, with nearly all studies reporting an imbalance in ROS and antioxidant activity, even under low-level exposure (Kesari et al., 2011; Lu et al., 2020; Yakymenko et al., 2016). The implication is potential cellular injury and genotoxicity.

Limitation	*Description*
Inconsistent exposure protocols	*Variation in modulation, duration, and SAR*
Lack of longitudinal studies	*Short-term effects dominate literature*
Heterogeneous biological endpoints	*Difficult to compare outcomes*

Table 3. *Common Methodological Gaps in Reviewed RF/MW EMR Studies*.

In contrast to early reviews that emphasized thermal thresholds only (ICNIRP, 1998), recent findings suggest non-thermal biological responses at lower intensities. For example, Nizhelska et al. (2020) found that mitochondrial activity was suppressed under exposures well below ICNIRP guidelines. These findings differ from those of Foster and Repacholi (2004), who reported no consistent biological changes under similar exposure levels.

Cumulative evidence also indicates that children and adolescents may experience stronger EMR effects due to thinner skulls and developing neural structures (Kheifets et al., 2005;
Schoeni et al., 2015). However, variations in study design and exposure metrics hinder direct comparison. Table 3 summarizes methodological limitations observed across reviewed studies.
These limitations underscore the need for standardized testing protocols and more rigorous, long-duration human trials.

Overall, the findings indicate growing evidence for non-thermal biological effects from RF/MW EMR exposure that may challenge current safety assumptions. While not all studies agreed on causality, the convergence of data across disciplines (animal, cellular, and human) strengthens the validity of observed trends.

Electromagnetic Principles and Interaction with Biological Tissues

Electromagnetic radiation in the radiofrequency (RF) and microwave spectrum spans frequencies from approximately 300 kHz to 300 GHz, corresponding to wavelengths from 1 km to 1 mm. This region is classified as non-ionizing, meaning the photon energy is insufficient to ionize biological molecules (ICNIRP, 2020). However, RF radiation can interact with tissues via electromagnetic induction, dielectric losses, and oscillating dipole effects (hhh; Barnes & Greenebaum, B., 2016).

Energy, Frequency, and Penetration

The **photon energy** of RF radiation is several orders of magnitude below the ionization threshold:

$E = hf = (6.626 \times 10^{-34}) \cdot f \ldots\ldots.(1)$ (Pall, 2018)

For example, Wi-Fi at 2.45 GHz has $E \approx 1.6\times10^{-24}$ J, which is biologically weak in terms of chemical bond disruption (Pall, 2018).However, **penetration depth** varies with frequency and tissue type, with lower frequencies penetrating more deeply into muscle and internal organs (Gandhi et al., 2012).

Specific Absorption Rate (SAR)

The specific absorption rate (SAR) quantifies the rate of energy absorbed per unit mass of tissue:

$SAR = \frac{\sigma \boldsymbol{E}^2}{\rho} \ldots\ldots\ldots\ldots\ldots.(2)$ (ICNIRP, 2020)

Where σ is tissue conductivity, **E** is electric field strength, and ρ is tissue density. SAR is the central metric used in exposure safety guidelines issued by (IEEE, 2019) and (ICNIRP, 2020), with regulatory limits typically set at:

- 2 W/kg (localized)
- 0.08 W/kg (whole-body average)

These values aim to ensure that tissue temperature rise remains under 1°C during continuous exposure.

Thermal Effects

Thermal interaction results from dielectric heating, particularly in high-water-content tissues. Alternating electric fields induce dipole rotation and ionic conduction, causing localized heating Foster & Repacholi, M. H. (2004).

Non-Thermal Effects

Non-thermal effects remain a subject of debate. Suggested mechanisms include:

- Modulation-specific neural responses (Panagopoulos et al., 2013)
- Membrane depolarization and calcium efflux (Pall, 2018)
- Reactive oxygen species generation and mild inflammation (Barnes & Greenebaum, B., 2016)

Such effects are often associated with low-intensity, modulated fields, and may not be reflected in SAR measurements alone.

Modulation and Biological Relevance

Biological systems may respond more strongly to **amplitude-modulated** or **pulsed signals**, even at the same average power level. Modulation patterns in GSM (2G), LTE (4G), and 5G NR differ significantly and may affect cellular electrophysiology or resonance processes (Halgamuge, 2020). Additionally, **wave polarization and coherence** may influence coupling efficiency in anisotropic biological structures (Barnes & Greenebaum, B., 2016).

Health Effects of RF/Microwave Radiation

Radiofrequency (RF) and microwave radiation have been associated with various biological and health-related effects. This section provides an overview of the major areas where RF/microwave exposure has been linked to health concerns. These include effects on sleep and circadian rhythms, potential impacts on fertility and reproduction, cognitive function disturbances, and possible carcinogenic outcomes. Each of these subtopics is explored in the sections below, based on the latest scientific literature.

Sleep and Circadian Rhythm Disruption

Sleep is a complex neurophysiological process regulated by circadian and homeostatic mechanisms. A growing number of studies indicate that RF EMR may disrupt these processes, even at exposure levels far below thermal thresholds.

Controlled laboratory research has shown that mobile phone exposure can affect sleep structure, notably by altering sleep spindle activity, REM latency, and overall sleep efficiency. For example, Regel et al. (2011) found that 900 MHz GSM signals modulate EEG during non-REM sleep. Similarly, Lowden et al. (2011) reported worsened sleep quality in individuals with self-reported sensitivity to mobile phone radiation.

Melatonin secretion—closely tied to the circadian system—is another physiological target. Wood, 2006(Wood, 2006) observed decreased nighttime melatonin levels following mobile phone and Wi-Fi exposure, indicating potential pineal gland suppression.

Epidemiological studies also support these findings. A Swiss cohort study found that adolescents using phones for more than 2 hours daily experienced reduced sleep duration and delayed onset Schoeni et al. (2017). However, variability in SAR reporting and modulation type across studies highlights a need for improved dosimetric standardization (Panagopoulos et al., 2013)).

Cognitive and Behavioral Effects

RF EMR may influence cognitive function through both acute and chronic pathways. Studies using EEG and behavioral testing have shown altered reaction times, memory deficits, and attention span reductions under RF exposure.

In human EEG studies, Jamal et al. (2023) reported modulation-specific changes in attention networks during cognitive tasks under 3.5 GHz exposure. In animals, (Narayanan et al., 2019) observed decreased exploratory behavior and increased anxiety in rats exposed to 10 GHz microwave fields.

Mechanistically, calcium efflux, oxidative stress, and neurotransmitter imbalance have been implicated (Crane-Molloy, 2024; Geesink & Meijer, 2020). RF-induced oxidative damage in the hippocampus appears to impact working memory and learning. Supporting, (Spandole-Dinu et al., (2023) found long-term memory deficits in mice after prolonged RF exposure.

Halgamuge, (2020) summarized these effects in a meta-review, emphasizing susceptibility in adolescents, whose developing nervous systems and thinner skulls allow for deeper EM wave penetration. However, not all studies show significant effects, particularly when SAR and waveform conditions are carefully controlled (Hosseini et al., 2019)

Neurological Symptoms and Mechanisms

Neurological complaints such as headache, dizziness, fatigue, and concentration issues are among the most frequently reported symptoms of RF exposure in both the general population and occupational settings.

Hardell&Nilsson (2025) compiled case reports from individuals living near mobile base stations, identifying patterns of chronic headache and cognitive fog consistent with the so-called "microwave syndrome." Samaila,(2024) and Crane-Molloy,(2024) suggest these symptoms are linked to cerebral inflammation, vascular instability, and altered neurochemical signaling.

Cellular studies show increased reactive oxygen species, glial activation, and cytokine release after RF exposure, which may compromise blood-brain barrier (BBB) integrity (Ubhenin et al., 2024; Jena et al., 2022). These effects are detectable at non-thermal SAR levels and are especially concerning with modulated signals in the 900 MHz to 2.4 GHz range.

EEG studies also demonstrate alpha and beta rhythm changes under exposure. Geesink, (2023) found desynchronization patterns in the frontal cortex of subjects exposed to mobile-like radiation fields, suggesting cortical rhythm entrainment.

The phenomenon of electromagnetic hypersensitivity (EHS) remains controversial. Some provocation trials show real, reproducible symptoms in sensitive individuals Heroux, (2025) while others attribute these effects to psychological factors. Vicnesh, (2025) 5)emphasize the importance of distinguishing physiological vs subjective outcomes.

Oxidative Stress and Inflammatory Mechanisms

Among the most consistent biological effects reported from radiofrequency (RF) and microwave radiation is oxidative stress, a cellular imbalance between reactive oxygen species (ROS) and antioxidant defenses. This imbalance can cause lipid peroxidation, DNA damage, and protein dysfunction, contributing to degenerative conditions and possibly carcinogenesis (Yakymenko, 2022).

Experimental data show that even low-intensity RF radiation—below thermal thresholds—can increase ROS production and reduce antioxidant markers such as glutathione (GSH), superoxide dismutase (SOD), and catalase. A review by (Samaila, 2024) noted that these effects are especially prominent in neuronal and hepatic cells exposed to 900 MHz to 2.45 GHz frequencies, often used in Wi-Fi and mobile communication systems.

Studies by Geesink&Meijer, (2020) demonstrate that non-coherent RF fields disrupt quantum coherence in cellular systems, leading to higher oxidative load. This view is supported by in vivo animal studies, which show tissue-specific elevation in oxidative stress biomarkers after mobile phone radiation exposure (Yakymenko, 2022).

Although acute inflammation is reversible, chronic low-level exposure may induce persistent microglial activation and neuroinflammation, which has been implicated in neurodegenerative diseases and behavioral deficits (Jena et al., 2022).

Some studies also highlight the potential protective role of antioxidants. Lai, (2014) suggests that co-administration of vitamins C and E, melatonin, or curcumin may mitigate RF-induced oxidative changes, though this remains an emerging field.

Safety Standards and Exposure Guidelines

Global safety standards for radiofrequency (RF) and microwave (MW) electromagnetic radiation (EMR) have been established primarily to prevent adverse health outcomes resulting from excessive exposure. These guidelines are primarily developed by international agencies such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2020) and adopted by organizations including the World Health Organization (WHO, 2007), the Federal Communications Commission (FCC) in the United States, and the European Committee for Electrotechnical Standardization (CENELEC). The foundational assumption of these guidelines is that biological harm arises chiefly through thermal mechanisms—that is, heating of tissue due to energy absorption.

The most widely accepted metric for evaluating RF exposure is the Specific Absorption Rate (SAR), which quantifies the rate at which electromagnetic energy is absorbed by human tissue, measured in watts per kilogram (W/kg). For the general public, ICNIRP recommends a SAR limit of 2.0 W/kg averaged over 10 grams of tissue, primarily to prevent thermal damage. However, non-thermal effects, such as oxidative stress, circadian disruption, and neurobehavioral changes, have been reported at SAR levels well below these thresholds, raising questions about the adequacy of current standards (Yakymenko et al., 2016; Zhang et al., 2022).

Despite growing evidence, existing regulations have not yet been updated to incorporate these findings. Moreover, exposure duration, modulation characteristics, and cumulative effects are often underrepresented in standard-setting frameworks (Panagopoulos et al., 2013). This reveals a critical research and policy gap: while current guidelines protect against acute heating, they may not sufficiently address chronic low-level exposure in real-world environments, particularly with the advent of 5G and ubiquitous wireless technologies.

There is a growing consensus among researchers that safety guidelines need to be re-evaluated in light of new biological evidence. Future revisions should integrate thresholds for non-thermal effects, account for modulation-specific and time-dependent risks, and consider vulnerable populations, including children, fetuses, and individuals with neurological sensitivity (Belyaev et al., 2016). Regulatory frameworks that fail to adapt may risk underestimating long-term public health impacts.

Overview of Regulatory Frameworks

Regulatory bodies such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Federal Communications Commission (FCC) have established safety guidelines for RF and microwave exposure based primarily on thermal effects—specifically, the Specific Absorption Rate (SAR), which quantifies tissue heating.

The ICNIRP 2020 revision maintains that adverse health effects are limited to temperature elevation above 1°C and does not acknowledge conclusive evidence for non-thermal biological effects Hardell et al. (2021). Similarly, the IEEE standard C95.1 (2019) also focuses on thermal thresholds as its key basis for exposure limits (Foster et al., Radio Frequency Exposure Standards, 2018).

Disputed Adequacy of SAR and Thermal Models

However, growing evidence from in vitro, in vivo, and epidemiological studies points toward biological changes at non-thermal intensities—such as oxidative stress, altered neurotransmitter levels, and genetic damage. Critics argue that SAR does not reflect real-time cellular dynamics, especially under modulated, pulsed, or low-frequency signals Bandara & Weller, (2017).

A major review by Crane-Molloy, (2024) called for a paradigm shift in exposure standards, stating that "current guidelines fail to protect from chronic low-intensity exposure effects seen in everyday wireless environments.

Policy Divergence and Precautionary Approaches

Some countries, including Italy, Switzerland, and Russia, have adopted stricter exposure limits than ICNIRP. These decisions are driven by precautionary principles and population-based epidemiological trends showing potential associations with cancer, fertility issues, and neurodevelopmental risks (Nyberg et al., 2024). There is a pressing need for updated safety metrics that consider cumulative exposure, non-thermal endpoints, and vulnerable populations (e.g., children, pregnant women).

Protective Strategies and Public Health Recommendations

As the ubiquity of radiofrequency (RF) and microwave (MW) electromagnetic radiation continues to grow with expanding wireless infrastructure, there is an increasing need for protective strategies that address both confirmed and potential health risks. While international safety standards primarily focus on thermal exposure thresholds, emerging evidence of non-thermal biological effects has prompted renewed concern among scientists, policymakers, and the public. This section outlines precautionary approaches, regulatory recommendations, and behavioral strategies aimed at minimizing chronic exposure, particularly among vulnerable populations such as children, pregnant individuals, and occupational groups. Emphasis is placed on practical, evidence-informed measures that support public health while accommodating technological advancement (Belyaev et al., 2016) (WHO, 2007)

Evidence-Based Public Health Strategies

The growing body of literature highlights multiple non-thermal biological effects of RF and microwave radiation (Hardell, 2017; Nyberg et al., 2024). This has prompted researchers and regulatory critics to call for proactive mitigation strategies. Key public health recommendations include:

- Reducing chronic exposure, especially in children, by limiting mobile device usage and Wi-Fi-enabled toys (McCredden et al., 2024)
- Implementing building codes to restrict RF penetration in schools and hospitals.
- Urban planning to reduce population exposure from 5G base stations, particularly in residential areas.

Technological & Engineering Protections

Advanced engineering approaches have been proposed to reduce exposure without impairing connectivity. These include:

- Adaptive antennas and beam forming to limit radiation zones (Gallucci et al., 2022)
- Passive shielding with carbon-based or ferrite-infused materials in homes and wearables (Héroux et al., 2023)
- Smart building designs integrating RF attenuation zones or "low-EMF rooms"
- Emerging studies show that protective clothing, such as silver-threaded fabrics, can attenuate field strength by over 95% in certain environments (Jeschke et al., 2022)

WHO, IEEE & EU

Recommendations

While the WHO maintains a conservative approach, it has acknowledged growing scientific uncertainty and supports the Precautionary Principle (WHO, 2007). The IEEE COMAR committee stresses voluntary reduction in RF use and improved public awareness campaigns (Bushberg et al., 2020).

In Europe, public health agencies have recommended:

- Delaying 5G rollout pending further risk evaluations
- Enforcing lower exposure thresholds in schools and nurseries
- Publishing real-time RF monitoring data for the public (Hardell, 2017)

DISCUSSION

This review examined the biological and health effects of prolonged exposure to radiofrequency (RF) and microwave (MW) electromagnetic radiation (EMR) below current thermal limits. The findings support the hypothesis that chronic, low-intensity exposure may elicit measurable biological effects. The most consistent outcomes were sleep and circadian rhythm disruption, oxidative stress, and neurobehavioral alterations, with weaker yet notable evidence for reproductive effects. Collectively, these results indicate that non-thermal mechanisms may contribute to EMR-induced biological changes, challenging the assumption that non-ionizing radiation is biologically inert below heating thresholds.

Comparison with earlier studies reveals both strong alignment and points of divergence. Similar to Yakymenko et al. (2016), this review found oxidative stress to be one of the most reproducible biological responses. Burch et al. (2002) also reported altered melatonin levels among mobile phone users, consistent with the sleep disruption identified here. Hardell and Carlberg (2013) observed neurobehavioral and neurological outcomes in human populations, which align with the current synthesis. However, some studies, such as Kesari et al. (2011), demonstrated more severe reproductive and oxidative damage in animal models than the present review suggests. Likewise, large-scale assessments summarized by the World Health Organization (2014) and ICNIRP (2020) concluded that health effects from everyday RF exposure remain uncertain, contrasting with this review's findings that suggest potential biological relevance even at sub-thermal levels. These discrepancies can be explained by differences in study design, duration, exposure intensity, and the influence of funding sources on reported results.

Several limitations should be acknowledged. First, much of the available data are derived from observational or short-term experimental studies, which restrict causal interpretation. Differences in experimental setup, exposure assessment, and biological endpoints also reduce comparability. Furthermore, a lack of standardized protocols and insufficient long-term human data make it difficult to establish definitive dose–response relationships. Publication bias and limited reporting transparency may also influence the overall strength of evidence, as studies with null results are often underrepresented.

Future research should address these gaps through large-scale, longitudinal studies that evaluate real-world exposure conditions and cumulative effects over time. Investigations focusing on vulnerable groups—such as children, adolescents, and pregnant individuals—are particularly important given their heightened exposure and potential biological sensitivity. Mechanistic studies at the molecular level are also necessary to clarify causal pathways, particularly regarding oxidative stress, membrane dynamics, and signal modulation effects. Additionally, future work should employ standardized dosimetric assessment methods and harmonized reporting criteria to improve reproducibility and comparability across studies.

In conclusion, this review underscores growing evidence that low-intensity RF/MW exposure may induce biological effects beyond thermal mechanisms. The findings align with several independent studies but diverge from regulatory assessments that emphasize thermal thresholds. While uncertainties remain, the cumulative evidence warrants greater precaution and a re-examination of current exposure standards to ensure public health protection in the era of expanding wireless technologies.

CONCLUSION

The increasing global reliance on wireless technologies has amplified public and scientific attention toward the potential health risks posed by radiofrequency (RF) and microwave electromagnetic fields (EMFs). Across decades of research, evidence has mounted for non-thermal biological effects including oxidative stress, genotoxicity, cognitive alterations, and possible carcinogenicity. Yet, these findings remain contested in regulatory frameworks that prioritize thermal-only exposure models like the Specific Absorption Rate (SAR).

Our review highlights that while international standards set by ICNIRP and IEEE have contributed to consistent global policies, they often fall short in addressing chronic, low-intensity, non-ionizing exposures that affect biologically sensitive populations. The lack of long-term epidemiological studies, standardized testing protocols, and independent funding continues to delay scientific consensus.

Importantly, this review supports calls for the precautionary principle in public health policy, particularly in school environments, urban planning, and occupational settings. Integrating non-thermal metrics, adaptive shielding technologies, and transparent public risk communication can serve as pillars of safer wireless ecosystems. International cooperation will be essential for harmonizing risk evaluation, updating outdated exposure limits, and guiding future research.

In conclusion, advancing our understanding of RF and microwave radiation requires multidisciplinary collaboration across physics, biology, public health, and engineering. Proactive measures based on current knowledge—not only absolute proof—must guide regulations to safeguard long-term public well-being in a rapidly digitizing world.

AUTHORS CONTRIBUTIONS

- Mohammad Rahim Sadeqi conceptualized and supervised the study.
- Mohammad Rahim Sadeqi investigated and analyzed data.
- Noor Mohammad Azizi wrote the manuscript with input from all authors.
- All authors reviewed and approved the final version.

ACKNOWLEDGEMENTS

I appreciate my colleagues and peers for their helpful discussions and encouragement throughout this work.

FUNDING INFORMATION

No funding is available for the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Data is available upon request.

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