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Review

Decarbonization through the Substitution of Fossil-Fuel-Powered Devices with Electromagnetic Devices: Exploring Exposure Effects on Public Health and Biodiversity

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Abstract: The heavy reliance on fossil fuels to meet society's growing needs has made greenhouse gases (GHGs) the primary drivers of climate change and public health problems. Consequently, substituting these energy resources in essential sectors such as transportation, industry, health, and communications is a priority to address these challenges. This substitution strategy involves the use of new, suitable devices, for example, replacing internal combustion engines with electric motors in transport vehicles. These new devices are expected to improve human well-being. However, their operation can generate negative side effects that must be monitored and mitigated. We therefore aim for a substitution strategy that could better safeguard human well-being. A significant portion of these adapted devices utilizes electromagnetic (EM) energy derived from the conversion of clean energy resources. They often produce emissions of unwanted electromagnetic fields (EMFs), particularly when using wireless technologies. This paper proposes a narrative review of selected literature related to the substitution of devices responsible for the greenhouse effect with EM devices where exposure effects are monitored and mitigated. To this end, it aims to study, highlight, analyze, and explore the effects of the corresponding EM radiation on public health and biodiversity. The different topics covered in this article are supported by specific instances from the literature facilitating understanding.

Keywords: decarbonization; atmospheric emissions; electromagnetic; wireless technologies; exposure effects; living organisms; electric mobility; telecommunications

1. Introduction

Humanity has always sought well-being. This quest has led to the exploitation of available energy resources—primarily natural and, for the most part, fossil-based. The progressive development of human society has been accompanied by the excessive consumption of these fossil fuels, which has proven destructive to the environment. This phenomenon has resulted in the greenhouse effect, threatening the lives of all living beings.

Recently, innovations have made it possible to replace fossil-fuel-powered equipment with systems fueled by clean energy sources—such as replacing internal combustion engines with electric motors in the transport sector [1]. This decarbonization, to be complete, must not be limited to electrification, but must consist of using the conversion of clean energy into electrical energy. A significant portion of these substitutions relies on electromagnetic (EM) energy, whether directly or through wired or wireless transmission. Although these devices do not emit greenhouse gases (GHGs), they can nonetheless give rise to adverse effects, particularly EM radiation. Such radiation can stem from the fields generated during wireless energy transmission, whether over short or long distances. Depending on the amplitude, frequency, and duration of exposure, this radiation may have harmful effects on public health and biodiversity.

In fact, the relationships between humans and other living organisms within their shared biodiversity constitute one of the oldest activities of civilizations. Most of these interactions—as is the case among all living beings—are mutually beneficial and contribute to general well-being. In addition to these beneficial interactions, daily human activities can have adverse effects on biodiversity, such as various forms of air pollution. These interactions between humans and biodiversity are generally observable in urban areas as well as in spaces dedicated to nature, such as parks, reserves, etc. [2,3]. Common EM devices are increasingly prevalent in these environments and emit EM fields (EMFs). Various living organisms, including humans, exposed to this radiation may experience impacts on their tissues and physiological functions. These effects may influence various species within biodiversity—humans included—in line with the "One Health" approach [4,5].

EM radiation can originate from man-made devices, natural sources such as sunlight, unexpected natural phenomena like lightning, or even the malfunction of household electrical appliances. Whether of natural or artificial origin, such radiation can have beneficial or harmful effects on the tissues of living organisms and on their intrinsic bioelectricity. This latter beneficial intrinsic property has been known since antiquity—notably to the Egyptians, who used the electric catfish of the Nile to relieve pain [6].

The most common sources of exposure of man-made EMFs associated with the substitution involved in decarbonization—which primarily concerns human mobility and connectivity—include wireless telecommunication devices, such as base station antennas (BSA) as well as wireless storage batteries charging devices such as those used in electric vehicles (EV) charging systems. Both categories emit fields, which are in the non-ionizing frequency range, and interact with objects in their environments. Such objects are mostly living organisms and electronic appliances. Such organisms consist of tissues of human as well as of other species in environmental biodiversity. In such a case, EMF exposure functions as an environmental stressor generating adverse biological effects (BEs) [7–9]. Relating to the perturbations of appliances, medical wearable and integrated tools are typical instances [10]. The two categories of exposure sources mentioned fall into two exposure modes: far-field exposure for wireless telecommunications BSA and near-field exposure for wireless charging devices for EV batteries.

BEs are closely linked to EMF exposure characteristics including the tissue biological and structural properties as well as the exposure source strength, frequency, mode (distance) and duration [11]. An EMF exposure in the non-ionizing frequency range for low frequency (LF) or radiofrequency (RF) causes typically induced tissue fields and a thermal BE produced by EM

energy dissipation in the tissue typified by the specific absorption rate (SAR) in W/kg, and the exposure duration [12]. For excessive high SARs and/or exposure durations, the dissipated energy can produce disproportional heating that can trigger more intricate non-thermal effects involving, depending on the tissue, different biochemical or bioelectrical disturbs of cellular, molecular and chemical arrangements in living tissues [13–15]. Besides these adverse artificial EMF radiations, some useful applications rely on natural or artificial radiation [16–19].

EMF management can be implemented in various ways depending on the circumstances. This may include the sustainable design of radiation-emitting devices, the shielding of exposed targets where appropriate, and/or the monitoring of EMF emissions—or even, in certain specific situations, avoiding proximity to radiation sources, such as the presence of living organisms near an electric vehicle during outdoor static battery charging [5].

This narrative review, focusing on the replacement of devices responsible for GHG emissions with reliable EM devices, aims to examine, highlight, analyze, and explore the effects of EMF exposure on public health and biodiversity, in relation to both near-field and far-field emissions. It will focus specifically on near-field exposure associated with wireless devices used in electric mobility and on far-field exposure associated with wireless telecommunication devices. This choice is not arbitrary: the replacement of the aforementioned systems primarily concerns activities involving movement—linked, on the one hand, to specific needs (work, medical care, education, visits, assisting others, etc.) and, on the other, to communication activities (discussions, meetings, conferences, scheduling appointments or making reservations, maintaining social connections, etc.). In this context, the substitution involves electric mobility—encompassing all types of EVs (urban, road, rail, maritime, aerial, etc.)—as well as telecommunication tools. Consequently, the effects of EMF exposure addressed in this study are limited to this scope; the analysis does not claim to cover every situation involving EMF exposure.

It should be noted that the analysis presented addresses a complex, multidisciplinary issue governed by several physical phenomena; various details regarding these—omitted from the text—are available in the cited references. Thus, the approach places the subject in context and focuses exclusively on the effects of exposure to EMF—and their management in relation to transmitting devices. The physical principles, design, and operation of these devices are described in the cited references. The article includes:

- GHGs and EMFs—Exposure Notion and Perturbation Management;
- Effects of EMF exposure on living organisms including beneficial effects, adverse thermal and other tissue effects, and perturbations of tissue-connected instrumentation;
- Physical phenomena and the governing mathematics including behavior of living tissues exposed to EMFs, bio heat tissues behavior following EM dissipation, and EMF–bio heat phenomena analysis;
- Near and far-field exposures on biodiversity involving applications on the effects of stray fields of wireless charging systems in electric mobility and effects of wireless telecommunication BSA as well as administration of near and far EMF radiations;
- Discussion and conclusions.

Numerous studies have been published on electromagnetic radiation from various sources with diverse characteristics (signal power, frequency, etc.). This article builds upon and enriches this earlier work by offering a key synthesis of analyses regarding human interactions in the context of the energy transition; it highlights improved telecommunications connectivity, combined with reduced travel and the use of clean modes of transport when necessary. The narrative review process involved a broad literature search and an exploration of references within peer-reviewed, English-language publications, drawing on various databases and publisher platforms—such as Google Scholar, PubMed, Nature, and Springer Link—and employing a range of search terms related to the article's themes. All references—including self-citations—are justified by the content requirements and have helped avoid textual repetition within the manuscript. Figures reproduced from external sources are used under a Creative Commons Attribution (CC BY 4.0) license or with permission from the original publisher, with the source duly acknowledged.

2. GHGs and EMFs—Exposure Notion and Perturbation Management

2.1. Substitution of Fossil Fuels

Fossil fuels are traditionally used for various forms of energy conversion (thermal, mechanical, electrical, etc.), primarily in electricity generation, industrial processes, and mobility-related applications. Replacing fossil fuels with more environmentally friendly alternatives entails widespread electrification based on clean energy conversion processes, as well as the adoption of equipment compatible with these new energy sources across the industrial and mobility sectors. As previously noted, mobility-related applications address essential needs regarding the transport of people and connectivity; this transition can be achieved through the use of EVs for transport and telecommunication tools for connectivity. Regarding connectivity, it is worth noting that the development of telecommunications makes it possible to eliminate the need for certain journeys.

2.2. EMF Exposure in the Context of GHG

The increasing availability of spatiotemporal data presents both opportunities and challenges for scientific research. In the environmental field—particularly regarding GHG emissions [20]—modern equipment such as GPS tools, remote sensing devices (stationary or portable), and satellite imagery enables the collection of data on environmental phenomena with exceptional spatiotemporal resolution, suitable for analyzing processes that evolve across both these scales. Such data allow for the prediction of concentrations of various current pollutants and the assessment of their dynamics across different areas [21–23]. Many studies have focused on analyzing emissions—the primary drivers of pollution and climate change—as they provide a better understanding of environmental degradation processes [24–26].

EM radiation can be considered, strictly speaking, a form of pollution, just like that produced by fossil fuels. However, the main difference between the pollution of these energy sources and EM radiation lies in the fact that the latter exists only in real time; that is, it depends on the presence of an active source. Consequently, EM radiation can only be detected spatiotemporally in real time, or in space at a given instant. This highlights a difference between the impact of fossil fuel-related pollution and that of EM energy on humans and biodiversity: in the former case, beyond direct exposure, the diffusion and accumulation of chemical pollutants in environmental elements (soil, water, air, etc.) continues to spread pollution to humans and biodiversity for some time—even after exposure has ended—whereas EM exposure ceases as soon as the source dissipates.

2.3. Perturbations of EMF Exposure and Their Management

This section describes the notion of exposure to EMF and ways to mitigate its effects. EM radiation can originate from an

intentional or unintentional source. The exposed object can also be an intentional or unintentional target. Useful radiations (see Section 3.1) occur when both source and target are intentional. Exposure disturbances typically occur with unintentional sources and targets. These are usually due to stray fields resulting from a malfunction, faulty design, or an uncontrolled state of the source device. This type of situation often involves near-field exposures, such as the wireless transfer of EM energy between a transmitter and a receiver separated by an air gap. Theoretically, an intentional source can radiate to an intentional target while simultaneously acting as an unintentional source for another unintentional target. This is common in far-field exposures, such as the wireless transmission of EM energy from an antenna to a communication device.

In the scenario described above, involving unintentional near-field sources and targets, exposure management can be achieved through the robust design of the source and target devices or via shielding strategies. Shielding consists of a thin sheet that absorbs and reflects EMFs; although theoretically positioned between the source and the target, in practice, it is attached to one or the other. A simple electrically conductive sheet usually suffices, though more sophisticated shielding may be used in specific situations [27]. When both intentional and unintentional sources and targets are simultaneously present in the far field, target protection is best achieved by monitoring the emitting sources. It should be noted that, in this case, shielding can impede energy transmission between the intentional source and the target; consequently, it can only be used on unintentional targets.

The effectiveness of protection against EMF exposure, including the immunity to EM interference (EMI), can be evaluated through EM compatibility (EMC) analysis. For example, the protection of target devices against EMF exposure via durable design can be accomplished by using structure materials immune to EMI or shielding, both of which can be verified by EMC routines (see Section 3.3).

3. Effects of EMF Exposure on Living Organisms

This section discusses direct and indirect impacts of EMF exposures on living organisms. As mentioned earlier, exposures on living organisms can be introduced by artificial or natural means and can be useful or unsafe for tissues as well as intrinsic functions. The effects of exposure to EMF vary depending on the nature of the field (intensity, frequency, etc.), exposure conditions, and the tissues exposed. As previously indicated, this study does not purport to cover all EMF exposure situations. Effects associated with ionizing frequencies fall outside the scope of this study, although they are mentioned very briefly. However, this article focuses on non-ionizing EM radiation (EMR) originating from LF sources in the near-field, or from single-frequency or pure RF sources in the far-field, which induce thermal BEs. Frequency-modulated artificial RF sources, which may cause observed non-thermal BEs, will be briefly discussed in Section 6.5.

3.1. Beneficial Effects of EMF Exposures on Public Health and Biodiversity

As previously mentioned, various useful applications rely on exposure to natural or artificial EMFs [16]. Natural EMFs—such as solar radiation—are essential to the lives of humans and other living organisms, particularly for energy production. Photosynthesis in plants, which converts sunlight into energy, is a prime example of this. Different light wavelengths have specific effects on plant development. Consequently, it is possible to modulate photosynthesis by using artificial light sources with controlled characteristics, intensity, and exposure durations in order to stimulate plant growth. Moreover, different investigations have been done on the EMR effects and its influence on robustness and germination of seeds, mineral nutrition, antinutrient factors, and nuisance prevention [18]. Furthermore, the hormesis effect of EMR (a defensive response to low doses of a toxic substance or ionizing radiation that may reduce their harmful effects) refers to the beneficial BE effects of low-dose ionizing radiation, which has been broadly used for sterilization of nutriment and natural composites physical adjustment in the bio industry [28].

Similarly, EMR can be used in medical examinations, such as imaging [29], as well as in therapies like hyperthermia—which offers effective methods for destroying cancer cells [17]—and other forms of radiotherapy [30,31]. Thus, as previously noted, it is important to study the specific effects of different types of EMR on living organisms in order to mitigate potential harmful effects while leveraging their beneficial applications, for instance in plant cultivation, food preservation [18], and seed germination [19].

3.2. Adverse Tissues Thermal BEs and Other Effects

Radiation from natural sources and man-made devices can cause harmful effects on the tissues of living organisms and on their intrinsic bioelectricity.

3.2.1. Induced EM–Thermal Fields BEs

The adverse tissue BEs are materialized by the induced tissue fields following near-field or far-field exposure to the external EMF (from a LF source or a single-frequency or pure RF source) as well as their corresponding SARs, tissue dissipated EM energy, and resulting temperature rise due to the conversion of this energy to heat. The significance of these induced electric–magnetic–thermal fields depends on the strength, frequency, nature (near or far exposure mode) and the exposure time interval of the external radiated EMF and the tissues properties. These induced fields can reach significant levels and may pose considerable risks. They are limited by thresholds fixed by safety standards [32–34].

Furthermore, when a living tissue is exposed to EMFs, a rapid, even instantaneous, increase in internal tissue temperature is observed, depending on the frequency magnitude. Living tissues possess a natural, generally superficial, thermal resistance to natural heat such as that of the sun. Under these conditions, heat propagates slowly by conduction within the tissues and by convection in the fluids that irrigate them. Conversely, under the influence of external EMR, depending on the frequency, these tissues and the fluids that irrigate them would be rapidly heated to a deeper level (see Section 6.3). In the case of tissues with low irrigation, this radiation can prove dangerous, depending on the characteristics of the source and the tissues. It should be noted that this frequency effect manifests itself differently depending on whether the exposure occurs in the near or far-field. Indeed, the higher the intensity and frequency of the field, the more pronounced this effect and the greater the impact on the tissue affected. Admittedly, this frequency effect can be mitigated by reducing the operating frequency of the source device, but this is done at the expense of the latter's performance.

The abovementioned EM–thermal BEs are the most common types encountered in everyday near- and far-field exposure scenarios. These BEs do not pose any risk if the tissue-induced fields related to exposure are consistent with the thresholds established by the abovementioned safety standards.

3.2.2. Non-Thermal BEs

As mentioned before, in the non-ionizing frequency range, disproportional SAR values (excessive tissue-induced fields) and durations can lead to potential non-thermal BEs. These can cause molecular disruptions leading to tissue harm [13,35–39]. Furthermore, unplanned EMF radiation in the ionizing frequency

range can cause adverse health effects linked to molecular disturbances concerning tissue destruction, owing to the high energy of photons or particles. Nevertheless, such ionizing radiation is commonly exploited in specific medical therapies, for instance, X-rays, whose energy level ranges from very low for dental care, to very high in irradiators planned to sterilize medical instruments. Figure 1 presents the ranges of ionizing and non-ionizing radiation, as well as details regarding RF radiation. The two categories of non-ionizing radiation (associated with low or high induced currents at LF or RF frequencies) and ionizing radiation reflect not only distinct frequency ranges but also differing energy levels that result in distinct atomic states: specifically, states without or with the formation of charged ions [40]. The case of radiation emitted by an artificial frequency-modulated RF source, producing observed non-thermal BEs, will be briefly addressed in Section 6.5.

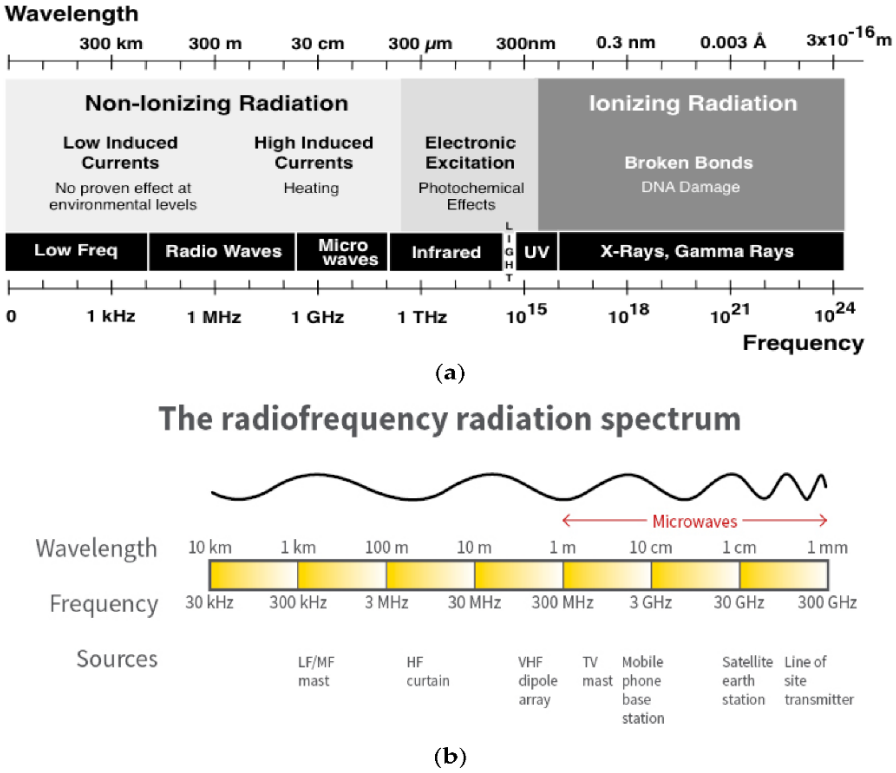


Figure 1. EMF frequency and wavelength ranges—reproduced from Ref. [40]. (**a**) ionizing and non-ionizing radiations, (**b**) detailed RF radiation.

3.2.3. People with Atypical Symptoms

Individuals may experience various unusual effects due to EMF exposure. These individuals will exhibit atypical symptoms [40], which fall into two distinct categories. The first involves some nonspecific symptoms caused by negligible exposures of short duration, well below the limits of safety standards. The second concerns cognitive disorders associated with long term exposure. About the first people's category, they are reputed to be hypersensitive to diverse frequencies of EMF in general. The cause of these symptoms is not confirmed. A number of studies have been published to assess this puzzling situation [41–44]. Regarding the second category, the origin of disorders of cognitive functioning is also unsubstantiated and diverse analyses have been stated in the literature [45–47]. Considering these explorations, these atypical symptoms appear real, and their manifestation is associated with EMF, even if their BEs appear missing. Given this contradiction, one can ponder that EMF effects currently unrecognized could emerge and elucidate such symptoms. It is scientifically difficult to exclude the possibility of a hazard. Such uncertainty justifies a cautious approach [48] and thus persons with these signs could reasonably be considered to have an enduring illness, while acknowledging that its central origin may be related to the EMF environment. It should be noted that the absence of BEs was based on the assumption of emissions from single-frequency wireless communication sources, whereas the observed "atypical symptoms"—like other non-thermal effects—appear to be attributable to artificial sources emitting RF for wireless communications, combining RF/MW (carrier), ELF, and ULF fields (see Section 6.5).

3.3. Perturbations of Tissue-Connected Instrumentation

This section concerns an indirect EMF exposure impact on living organisms and particularly humans. This is related to perturbations of healthcare instrumentation devoted to general supervision of basic life functions. Tissue-connected therapeutic tools are devices positioned near or incorporated into the body, including wearable, removable, embedded or imaging devices. They permit observation, prediction, maintenance, stimulation, and more. They can perform passive or directed tasks in tissues correlated to detection or assistive actions. Moreover, these tasks can be exclusive or collaborative, autonomous or remotely guided, and perform in real-time ceaselessly.

Detecting tasks can use wearable tools working in real-time for the continuous supervision of central health data, allowing staff to combine reliable and accurate awareness, as well as authorizing patients to accomplish their daily activities while staying monitored. Different investigations on sensing duties have been reported in literature, for example, for detection and diagnosis [49–52], as well as for monitoring and handling [53–56]. These were related to different healthcare tasks such as, health management and forecasting, heart rate monitoring, respiratory monitoring, blood pressure control, personalized pain management, and more.

Assistive tools embrace various operational classes, such as tissue-embedded devices for maintenance and stimulation, tissue

enclosing for image-guided intervention, and sensorimotor deficiencies of superior and inferior limbs assistive devices. These involve, for example, pacemaker and defibrillator stimulation [57], integrated drug release tools [58], implanted spinal cord control [59], regular cardiac blood stream assisting [60], magnetic resonance imaging (MRI)-assisted interventions supporting [61] and limbs with sensorimotor deficiencies assistance [62–64].

The abovementioned detecting and assistive tools, should be protected from different EMRs confirming their immunity to EMI. This can be accomplished by keeping out of EMF-sensitive materials, thus using materials immune to EMI, inside or close to the tool or shielding the tool when possible. Indeed, EMI can disturb the tool field, such as in an MRI scanner (for more details, see Section 6.1), or the tool operation because of its inner EMF-sensitive materials. These disturbances can affect individuals equipped with wearable skin-sensing devices and integrated assistive tools [65], for example in cases involving integrated active devices [66,67]. The corresponding immunity can be verified using experimental EMC protocols [67] or through numerical assessment [68].

3.4. Impact on Intrinsic Functions

This section briefly discusses intrinsic bioelectricity in living organisms and its possible stress by exposure to external EMFs. A natural electric activity in the tissues of living organisms can be produced by tissue-existent ions and electrons connected to the properties of cell membrane and electron carrier sequences of respiration and photosynthesis. Such activity is associated with the coordinated neuromuscular action responsible for motor function in humans and animals, with parallels in plants [69,70].

Essentially, single-celled organisms, animals and plants face several of the same problems. The most fundamental challenge is ensuring the energy required for life, reproduction, protection and adaptation. In order to survive and reproduce, living organisms at all levels of organization need to communicate internal and external signals to regulate energy balance in changing environment. At the simplest level the electrical interaction works commonly for intra/inter-cellular, tissue-to-tissue and being-to-being communication.

For example, in plants, solar energy is vital for their functioning and, consequently, the combination of electrical signals and other signs related to energy absorption constitutes an important process that universally oversees plant homeostasis. Diverse commitments of plant electrophysiology comprising ionizing radiation effects, energy excess absorption, in addition to questions associated with plant adaptation, precision agriculture, and infectivity can be found in the literature [71–76]. Furthermore, different disturbances can be detected, for instance, EMFs disturb ion channels, potential of membrane or Ca^{2+} signaling [77], plants electrical signaling and long-distance communication [78], problems correlated with the rate of photosynthesis, light respiration, and adaptive responses of plants to light stress [79,80], and effects of long-term low-level EMFs on ecosystem-level [81].

4. Physical Phenomena and the Governing Mathematics

This section deals with non-ionizing EMR from LF sources in the near field or from single-frequency or pure RF sources in the far field. When a material is exposed to an EMF, induced fields appear in the exposed area (near-field) or throughout the entire structure (far-field). These induced fields depend on the intensity and frequency of the source field, as well as the local EM properties of the material, namely its electrical conductivity and permittivity, and its magnetic permeability. These induced fields result in EM energy being absorbed by the material, corresponding to the energy emitted by the source. This dissipated energy is converted into heat, leading to a rise in the material's temperature through a heat transfer process.

In living tissue, the relevant phenomena are electromagnetic, thermal, and biological. Living tissues are generally composed of solid structures irrigated by fluids necessary for their functioning. In living organisms these fluids are mainly blood in animals and sap in plants (see Section 6.3). The biological–heat transfer behavior is closely linked to the convective transfer in the fluid irrigating the tissue. Thus, these two phenomena can be associated in a bio heat (BH) process. The outcome of this process depends on the local BH properties of the tissues, namely thermal conductivity, specific heat, density, and convective heat transfer parameters in the fluid irrigating the tissue. The overall EMF exposure of living tissues can be represented by a coupled EM–BH phenomenon, with energy dissipated by the EM field serving as a heat source for the BH process.

4.1. Conduct of Living Tissues under EMF Exposure

The local EM response of living tissues under EMF exposure described above can be represented by the combined electric and magnetic fields, expressed through the EMF harmonic formulation (customized for exposure conditions), which is established on Maxwell's local EM field equations [82], under its differential form:

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{1}$$

$$\mathbf{J} = \mathbf{J_e} + \sigma \mathbf{E} + j\,\omega\,\mathbf{D} \tag{2}$$

$$\mathbf{E} = -\nabla V - j\,\omega\,\mathbf{A} \tag{3}$$

$$\mathbf{B} = \nabla \times \mathbf{A} \qquad \text{with } \nabla \cdot \mathbf{A} = 0 \quad \text{(Coulomb gauge in the quasi-static near-field case)} \tag{4}$$

In Equations (1)–(4), **H** and **E** are the magnetic and electric field vectors in A/m and V/m, **B** and **D** are the magnetic and electric induction vectors in T and C/m^2, **A** and V are the magnetic vector potential and electric scalar potential in Wb/m and volt. **J** and $\mathbf{J_e}$ are the total and source current density vectors in A/m^2, σ is the material electric conductivity in S/m, and ω is the angular frequency = 2πf, f is the frequency in Hz. The symbol **∇** is a vector of partial derivative operators. The magnetic and electric material constitutive laws, respectively, between **B/H** and **D/E** are signified by the magnetic permeability μ and the electric permittivity ε in H/m and F/m.

The solution of Equations (1)–(4) allows the computation of the various distributions of the local values (see Section 4.3) of the induced fields in the involved tissue segment as well as those of the local dissipated EM power. The specific value of this power is given by:

$$P_d = \sigma_{eff}\, E^2/2 \qquad \text{with} \qquad \sigma_{eff} = \sigma + \omega\, \varepsilon'' \tag{5}$$

In Equations (5), E is the induced electric field (absolute peak local value) in V/m, ε″ is the imaginary part of the complex permittivity ($j\,\omega\,\mathbf{D} = j\,\omega\,(\varepsilon' - j\,\varepsilon'')\,\mathbf{E}$), and P_d in W/m^3. The quantities $\omega\,\varepsilon''$ and σ are related respectively to the dielectric and conducting loss (frequency dependent); for very high frequency $\sigma\,E^2/2$ is insignificant relative to $\omega\,\varepsilon''\,E^2/2$ and conversely for very low frequency and the corresponding SAR value is given by ($SAR = \sigma_{eff}\,E^2/(2\rho)$, W/kg).

4.2. Behavior of Bio Heat Tissues Subsequent to EM Dissipation

The local bioheat effects in living tissues resulting from the EM dissipation described above can be represented by the conventional heat transfer equation adjusted by adding the biological self-tissue metabolic heat source, the specific EM power dissipation heat source and the convective transfer in the fluid irrigating the tissue. For animal tissues, the BH equation including metabolic heat and convective heat transfer in blood is given by

the Pennes bio-heat equation [83]. A broad-spectrum form of such BH equation under its differential form can be given by:

$$c\,\rho\,\partial T/\partial t = \nabla \cdot (k\,\nabla T) + P_d + P_t + c_f\,\rho_f\,p_f\,(T_f - T) \quad (6)$$

In Equation (6), c is the tissue specific heat (at constant pressure) in J/(kg °C), ρ is the density in kg/m^3, k the thermal conductivity in W/(m °C), and T local temperature of tissue in °C, P_t (animal or plant tissues metabolic heat), P_d is given by Equation (5). The last term in Equation (6) denotes the convective heat transfer via irrigating fluid (blood for animal and sap for plant), T_f, is the fluid temperature in °C, and c_f, ρ_f, and p_f are, respectively, the fluid specific heat in J/(kg °C), the fluid density in kg/m^3, and the perfusion rate in 1/s.

4.3. EMF–Bio Heat Phenomena Analysis

The two EMF and BH phenomena characterized by Equations (1)–(4) and (6) are locally interdependent and are coupled via the dissipated EM specific power P_d given by Equation (5). Furthermore, their solution must consider the specific features of the concerned tissues. These features—topological complexity, tissue inhomogeneity, nonlinear variable behavior and their interdependence—all call for advanced computational approaches. Addressing these features requires a local description of the tissue using discretized 3-D techniques such as the finite element method (FEM) or comparable methods (BEM, FDTD, etc.) [84,85] associated with fitting equations coupling schemes. Consequently, a weakly coupled iterative procedure to solve the EMF and BH equations, accounting for their widely differing time constants, can be implemented using Equation (5).

5. Near- and Far-field Exposures on Biodiversity

This section will address the aforementioned adverse effects in the context of common applications involving near-field and far-field exposure. Two representative cases of these exposure categories will be examined: the near-field of wireless charging systems for EV batteries and the far-field of wireless telecommunication BSA.

5.1. Effects of Stray Fields of Wireless Charging Systems in Electric Mobility

In the field of electric mobility, EVs that are not connected to the grid (autonomous vehicles) are equipped with the energy storage batteries required to power the electric motor. These vehicles rely on charging systems to replenish their storage units, whether the vehicle is stationary or in motion. These systems may utilize either wired or wireless connections. Wired connections are suitable for overnight charging while the vehicle is parked. However, for other scenarios—such as dynamic charging (electric roads) [86], short-duration static charging at home or work [87], or static charging during brief stops (public buses) [88]—wireless charging is the preferred method. These systems enable wireless power transfer (WPT). In the case of EVs, these systems employ inductive power transfer (IPT). An IPT system comprises a core component consisting of an inductively coupled transformer (ICT), which is inserted between the electrical grid and the storage batteries and connected to them via static electronic matching converters [87,88].

The ICT consists of two coupled coils—transmitter and receiver—separated by an air gap. The transmitter is fixed externally (usually on the ground) and connected to the grid, while the receiver is mounted on the vehicle (usually under the chassis) and connected to the storage batteries. The air gap results in weak coupling between the coils; consequently, the active power transferred via the ICT involves significant reactive power, leading to a poor power factor. Therefore, the two ICT coils are compensated using capacitors to achieve an effective power factor. Consequently, IPT enables energy transfer with galvanic isolation via a capacitively compensated ICT, allowing resonant operation that ensures reliable efficiency. The details of the full IPT device can be found in Ref. [87] and the first figure in Ref. [88]. Figure 2 illustrates a schematic of an ICT. The coupling coefficient and the resonant frequency of the two tuned resonant circuits (with series-series compensation, [5,87]) of the transmitter and receiver coils are given by:

$$k = M_{12} \cdot (L_1 \cdot L_2)^{-1/2} \quad (7)$$

$$\omega_o = (L_1 \cdot C_1)^{-1/2} = (L_2 \cdot C_2)^{-1/2} \quad (8)$$

Where L_1, L_2 and M_{12} are self and mutual inductances of the ICT coils, and C_1 and C_2 are their compensating capacities.

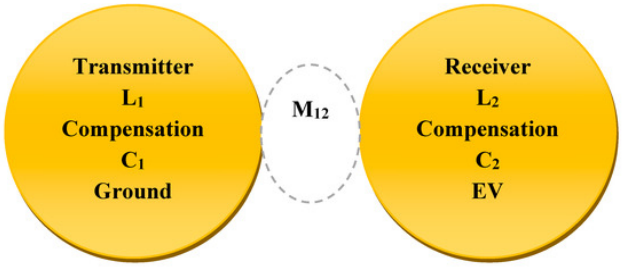


Figure 2. Schematics of a compensated ICT in EV IPT—reproduced from Ref. [5].

WPT systems can generate EMR characterized by near-field EMI, which may pose risks to vehicle passengers, nearby individuals, or surrounding biodiversity [8,89]. When passengers are inside the vehicle—such as during dynamic charging (on electric roads) [86] or static charging during brief stops (e.g., public buses) [88]—they are protected by shielding. In the case of short-duration static charging at home or the workplace [87], the vehicle is typically unoccupied; the risk associated with EMI then concerns people in the vicinity or the surrounding biodiversity. Consider, for instance, a WPT system installed between an EV chassis and the ground, operating during battery charging in an open area (without passengers): this ground-based charging mode poses a threat to surrounding populations and biodiversity. Figure 3 illustrates various scenarios corresponding to these high-risk situations [90]. This EMI is associated with leakage fields from the WPT system's coupled coils—driven by the air gap distance—and can be amplified if the coils are misaligned [91,92]. In such situations, the fields induced in tissues can be controlled to ensure compliance with safety standard limits [32].

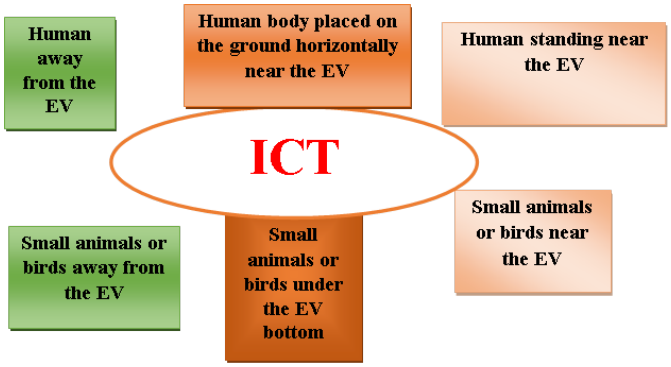


Figure 3. Qualitative schematic examples of typical situations in which ICTs pose a risk to surrounding populations and to domestic animals and wildlife. The colors indicate risk: the closer to red, the higher the risk.

Figure 4 exhibits an illustrative case of EMF exposure from an ICT, corresponding to the abovementioned open space (without passengers) ground-based charging, on a human body placed on the ground horizontally near the vehicle [11]. This body position corresponds to the worst-case scenario for humans and is often used to verify compliance with safety standards thresholds.

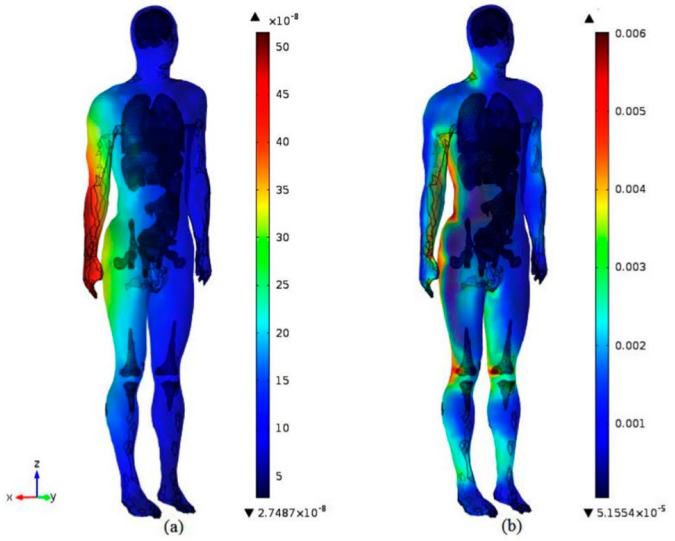


Figure 4. Induced fields' distributions in the human body, owing to an ICT under EV, for horizontal, ground lying body alongside the EV—reproduced from Ref. [11]. (**a**) Magnitude of magnetic flux density B (T), (**b**) Magnitude of electric E-field (V/m).

The figure shows the spatial distribution of magnetic flux density (B) and electric field strength (E) induced in the human body following exposure to leakage fields from an ICT system (3 kW at 30 kHz) [11,87,93]. The 3D values of the B and E fields, calculated using Equations (1) to (4) for this situation, were verified by comparison with the limits of the aforementioned safety standards [32] (27 μT for B and 4.05 V/m for E, applicable since 2010). The calculated values were in compliance with these safety thresholds. It may be noted that these calculations are commonly accomplished using phantoms (numerical virtual body models) that match correctly the expended local field calculations via the discretized approaches mentioned in Section 4.3; these reflect truthful high-resolution representation of tissue [94,95]. It should be noted that, although this issue relates to thermal BEs, verifying compliance with safety thresholds does not require calculating the SAR or the temperature rise, as these depend on the field values (SAR = σ_{eff} $E^2/(2\rho)$, in W/kg) used for such verification.

5.2. Effects of Wireless Telecommunication Antennas

Different nature-oriented spaces, for instance areas, have room for people in offices, universities or schools, museums, clinics, relaxation areas, kindergartens, parks, and more. These places may host adults, children or domestic animals at established schedules during the course of the day, week, and season. Such places are incorporated in nature-oriented spaces, which hold their individual biodiversity. Up-to-date administration of these places can make the most of being connected through antennas to ensure their management, safekeeping and telecommunications requests. Such connectivity is undeniably appreciated, but its impact on the neighborhood population and other species of the bordering biodiversity necessitates special attention. Certainly, it may have undesirable effects not only on the living organisms voluntarily or involuntarily at the site through its operational hours, but also on all living organisms in the neighboring area over a long term [9]. Addressing these challenges requires managing coverage areas, antenna emission orientation, and the temporal aspects of their operation. Connectivity is provided by BSA transmissions, which enable structured coverage but generate EMR in the non-ionizing RF range (assuming a single-frequency or purely RF source).

The RF radiation emitted by the BSA is characterized by far-field EMI. This radiation differs from that described in Section 5.1, which was near-field and could be attenuated by shielding protecting the exposed materials. In the present case, given the expected emissions from the BSA, shielding is not feasible. The only way to protect living organisms in the environment of the site from exposure is to manage their space in parallel with spatiotemporal management of BSA emissions. In this way, the BSA dual coverage–exposure can be regulated to allow for reliable spatiotemporal thinning. Emissions would then occur only in the intended locations and at the intended times, thus ensuring the protection of public health and biodiversity. For example, in the case of a park, Figure 5 illustrates the emission restriction categories in three different areas, park administration with high emission, visitors' area with moderate or zero emissions, and environmental area with low or zero emissions [96]. Indeed, exposure can be adapted both inside and outside the park according to spatial and temporal restrictions. Inside the park (red and yellow arrows in Figure 5), spatial management limiting emission coverage to specific areas and times is necessary, while in the park surrounding areas (green arrow), emissions are kept to a minimum.

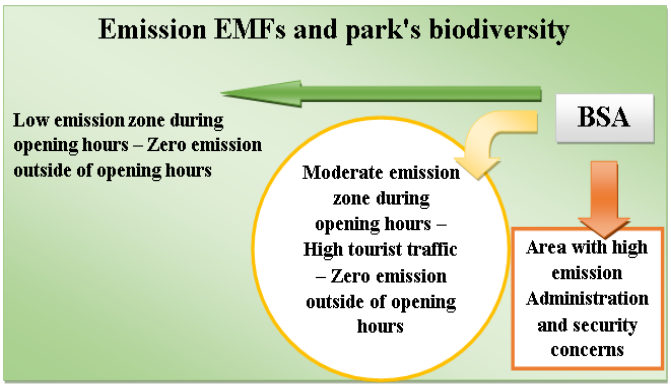


Figure 5. Schematics of spatial arrangement of a nature park's organization accounting for park and BSA spatiotemporal operational conditions—reprinted with permission from Ref. [96].

6. Discussion

In the reviews and analyses developed in the preceding sections, a number of points deserve further discussion, or certain related details may facilitate reading.

6.1. EMI Perturbation of Healthcare Instrumentation

This section addresses RF field disturbances in an MRI scanner caused by exposure to an external EMF or the insertion of EMF-sensitive materials. MRI scanners are known to be installed in shielded rooms and protected against external interference. However, their structure may contain EMF-sensitive substances that can disrupt their intrinsic fields, particularly the RF field. This issue can arise with MRI-guided therapeutic tools, such as robotic surgical procedures or drug delivery. In such cases, robotic devices and interventional tools introduced into the scanner structure must be free of EMF-sensitive materials (magnetic materials and solid conductors), thus only MRI-compatible materials can be used. This difficulty stems primarily from the robotic device that actuates the operation. Most actuators that meet the necessary strength and response-time requirements are not MRI-compatible. However, adapted piezoelectric actuators can be a suitable solution, but their EMI immunity must be checked by EMC analysis

as described in Section 3.3 and illustrated in the fourth figure of Ref. [68].

6.2. Smart Digital Monitoring of Near and Far EMF Radiations

Sections 5.1 and 5.2 addressed near-field and far-field radiation problems, respectively. We observed that both devices studied exhibit intended objectives and undesirable side effects related to radiation. Generally, the operational goal of these devices is to improve the expected outcome while mitigating side effects. This can be achieved through sustainable design [97,98] and/or shielding [27,99] or operational management [88,96], depending on the context. In the latter case, the relevant autonomous procedures can be monitored as part of a network (electrical or telecommunications network) using intelligent digital tools. Moreover, protecting public health and potentially affected biodiversity from near-field radiations can be achieved by source distancing of ICT and EVs from living organisms (see Section 6.4). The device of Section 5.1 can be assisted and monitored through smart digital tools, thus accounting for EMI safety and ecological environment. In this case the autonomous procedure including the connected EV–IPT–grid, accounting for EMI security can be assisted by an artificial intelligence (AI) algorithm helping decision-making [100–103] and supervised by digital twin (DT) implementation ensuring uncertainty and complexity mitigation [104–107]. The details of such management could be found in [88] and are summarized in Figure 6.

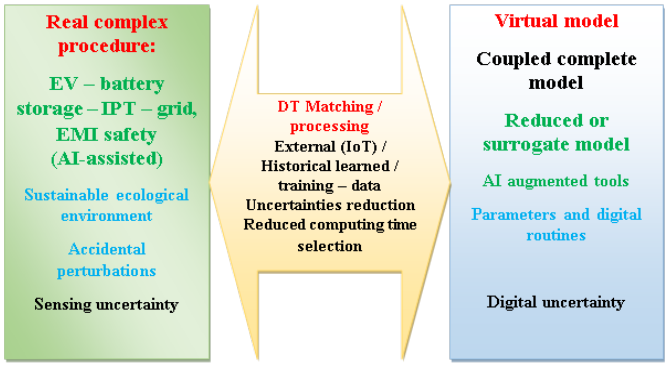


Figure 6. DT monitoring scheme of the complex controlled procedure including the connected EV–IPT–electric network, taking into account EMI safety and AI assistance, enabling EVs to operate in an ecological environment—reproduced from Ref. [88].

Concerning the device of Section 5.2, a similar assisted and supervised autonomous emitting–exposure procedure ensuring the protection of public health and potentially affected biodiversity can be accomplished. The details of such management could be found in [96].

6.3. EMF Exposure on Animal and Plant Living Tissues

The term "living tissues" denotes tissues constituted of solid structures associated with soft substances, perfused by liquids that guarantee their function. The principal living tissues considered here are those of animals and plants. The corresponding soft substances are the veins and arteries that carry blood in animals, and the xylem and phloem that transport sap in plants. Such conceptual analogy is shown in Figure 7. It should be noted that such an analogy does not account for the precise differences between the biological characteristics of blood dynamics and those of sap dynamics.

Such living tissues are sheltered by an outer thin layer opposed to natural assaults such as sun, frost, wind, etc. When confronted with natural sun heating, typified by conductive heat transfer through the outer layer and by convection in the irrigating liquids, the tissues' self-defense is well adjusted. Conversely, this self-defense proves ineffective against the thermal BEs induced by EMF exposure particularly with higher frequencies, as the tissues are not adapted to such exposure [108–112]. Indeed, such EMF radiation has two specific features: the direct dissipation of EM energy in the internal layers of the tissues [113] and its capacity to heat tissue in an instantaneous manner [11,12]. It is worth noting that in the event of overheating of the internal layers, only tissue irrigation with fluids can counteract this, and that deficient irrigation would be dangerous to the affected tissue (see Section 3.2.1).

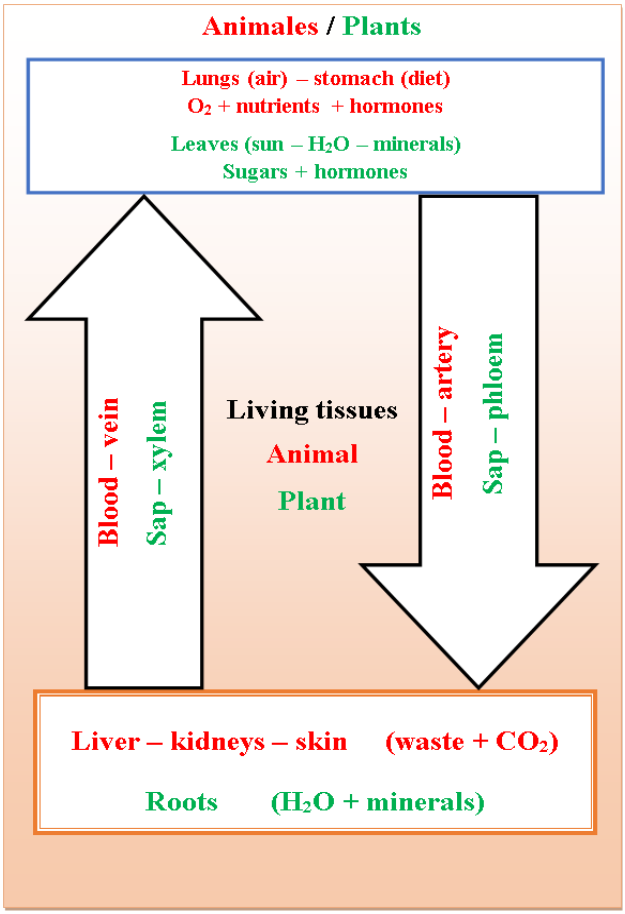


Figure 7. Schematic demonstration of a conceptual analogy of xylem and phloem enfolding the sap in plants (**green**) and veins and arteries enclosing the blood in animals (**red**)—reprinted with permission from Ref. [96].

6.4. Public Health and Potentially Affected Biodiversity Protection through ICT Distancing

As mentioned in Section 6.2, protecting public health and biodiversity from near-field radiations can be achieved by maintaining a safe distance between source ICT of EVs and living organisms. In practice, where charging is carried out with unoccupied EVs (static ground-based charging in open space, see Figure 3) or EVs with an internal protective shielding while momentarily stationary (static ground-based charging in bus stops), people and other living species outside the EV in open space or people on the platform or boarding in bus must be protected. In such cases, EV external shielding is basically impossible because of the disposition of the ground-based ICT. Only responses such as restricting the EV in open space or shifting the bus ICT further away can be viable. For instance, a charging tool installed on the bus roof can be used during a stop at the end of a journey, when there are no passengers (see Figure 8), thus protecting living species on the platform or nearby the bus [90].



Figure 8. A rooftop charging tool during the terminal stop when the bus is unoccupied—reproduced from Ref. [90].

6.5. Observed Non-thermal BEs of EMR from Man-made Wireless Communication Systems

Wireless communication (WC) systems utilize emissions in the non-ionizing RF range (from 300 kHz to 300 GHz). Two categories of emitting sources can be considered: a pure-frequency source (natural wave)—without modulation or pulsing—whose signal consists solely of the RF carrier wave; and a polarized, coherent source—corresponding to the man-made RF emissions associated with WC systems—whose signal includes, in addition to the RF carrier wave, modulations or pulses at extremely low frequencies (ELF) or very low frequencies (VLF). The BEs associated with first category are considered thermal (see Section 4), whereas those associated with the second category are, based on observation, considered non-thermal and are briefly described here.

It has been repeatedly emphasized that modulated or pulsed RF EMFs are markedly more bioactive than unmodulated or non-pulsed fields—all other things being equal—and that most of the observed effects are non-thermal in nature [114]. Consequently, the observed non-thermal BEs of EMRs associated with RF WCs are largely related to the ELF modulation or pulsation they incorporate. Numerous experimental results suggest a link between the exposure of laboratory animals or cells to artificial EMR—whether ELF fields or broadband WC systems—and oxidative stress (OS) resulting from the overproduction of reactive oxygen species (ROS), as well as genetic damage or alterations (DNA lesions, chromosomal abnormalities, mutations, etc.), cellular senescence (cellular aging and loss of replicative capacity), cell death, and other related effects [115–120]. More specifically, numerous experimental laboratory studies (in vivo or in vitro) have documented, particularly in recent years, the induction of OS and/or cellular senescence [121–127].

6.6. Qualitative Illustration of the Energy Transition's Impact

The underlying principle addressed in this article is that substitution shifts the burden associated with greenhouse gases toward electromagnetic fields. Consider the case of replacing internal combustion engine vehicles (ICEVs) with electric vehicles (EVs). The analyses presented in this article indicate that, by adhering to certain guidelines, it is possible to mitigate potential disturbances caused by electromagnetic radiation. We can thus assess the pollution reduction achieved by replacing ICEVs with EVs.

By way of illustration, according to the International Energy Agency (IEA) [128,129], the lifecycle emissions of a mid-sized EV are nearly half those of an equivalent ICEV. The IEA indicates that the net avoided GHG emissions (based on a "well-to-wheel" approach) resulting from EV deployment are significant, with substantial reductions expected between 2023 and 2035 under various scenarios [128]. Figure 9 shows that, under the Stated Policies Scenario (STEPS), net avoided GHG emissions will reach nearly 700 million tonnes of CO_2 equivalent by 2030; even greater reductions are expected under the Announced Pledges Scenario (APS) and the Net Zero Emissions by 2050 Scenario (NZE). This highlights the potential for EVs to generate significant emission reductions as electricity grids decarbonize [130].

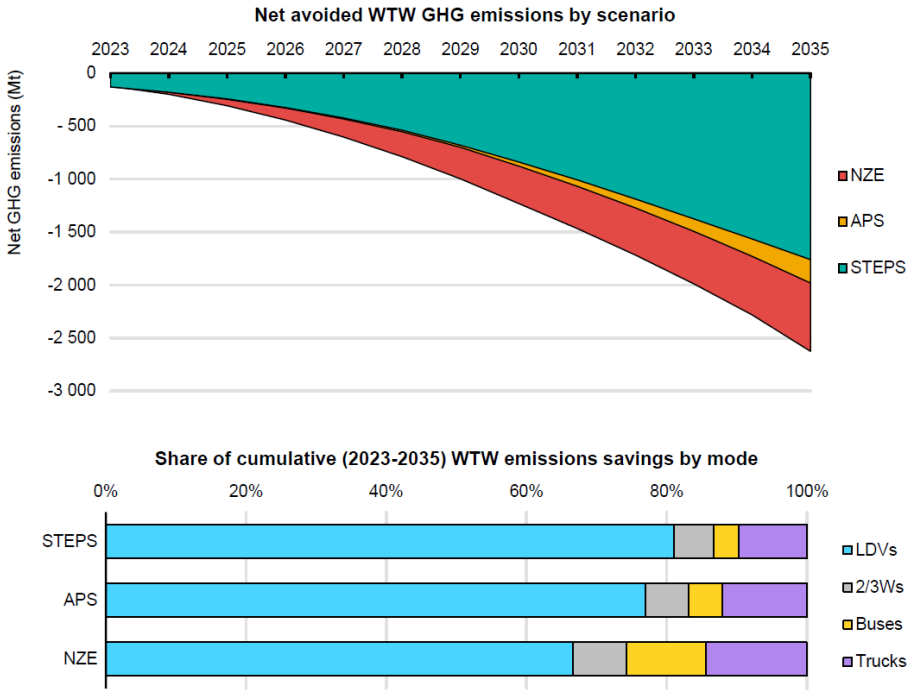


Figure 9. Net reduction in well-to-wheel GHG emissions from EV employment, specifying the percentage of emissions avoided by mode, from 2023 to 2035—reproduced from Ref. [128]. Licensed under CC BY 4.0. LDVs = light-duty vehicles; 2/3Ws = two/three-wheelers; WTW = well-to-wheel.

6.7. Current Status and Limitations of Existing Safety Standards

Current international standards for human protection—discussed in this article and elsewhere—cover both near- and far-field exposure across a wide frequency range. However, they do not fully account for the risks associated with EMR generated by recently developed technologies. A case in point is the issue addressed in Section 6.5 regarding the observed non-thermal biological effects of EMR from anthropogenic wireless communication (RF) systems, specifically those associated with the ELF modulation or pulsing they incorporate. Furthermore, there are no standards for protecting non-human species that are part of biodiversity; consequently, the "One Health" concept—which links biodiversity protection to human health—is not taken into consideration.

It is suggested that the necessary revision of standards should systematically incorporate the latest findings regarding risks to humans, including individuals exhibiting atypical symptoms, and integrate the "One Health" concept within the human environmental ecosystem, as well as an information and education component for users of EM equipment.

6.8. Future Research Perspectives

Decarbonization aims to harness clean energy conversion for electrification. Therefore, for reliable and carbon-free conversion, the operation of EM devices must be coupled with intelligent planning tools that enable optimal use of clean energy. This topic warrants further investigation.

Protection thresholds for humans are specified in Section 3.2.1, whereas for non-human species such thresholds are not generally determined, due to the wide-ranging morphological and anatomical diversity between species [131]. It is important to assess classified thresholds for various species to control the effects of exposure and thus preserve potentially affected biodiversity.

The potential effect of EMF exposure on the intrinsic electrical activity of living organisms [69,70] is briefly addressed in Section 3.4. Actually, one of the key modes of communication in living organisms depends on electrical signals, permitting the transfer of information inside and between organisms over long distances, for example in plants [132]. Future efforts on this topic could focus on integrating plant electrical activity into environmental supervision, and on studying its disruption by EMF radiation [133–135].

7. Conclusions

In the present paper the objective of replacing devices responsible for the greenhouse effect with reliable EM devices has been investigated. The effects of exposure to EMFs on public health and potentially affected biodiversity have been highlighted, analyzed and explored. The main conclusions of this paper can be summarized as follows:

- Decarbonization is undoubtedly essential; it also involves converting clean energy into electrical energy. Consequently, to ensure reliable, decarbonized conversion, it is necessary to manage EM side effects and uphold the "One Health" concept;
- The "One Health" approach is an information and education concept aimed at users of EM devices, that is, all social classes, all ages, etc.;
- Mitigating the side effects of devices that emit EMFs can be achieved through sustainable design and/or shielding, or through operational management utilizing smart digital tools, depending on the context. The more a device protects public health and potentially affected biodiversity, the higher its cost; however, this remains preferable to problematic effects with costlier consequences;
- With the advent of smart cities, their electric mobility, and modern telecommunications, the use of associated managed wireless technologies will have positive impacts on public health and potentially affected biodiversity. These technologies will be essential to supporting the ecosystem necessary for the development of mobility and telecommunications systems, thus contributing to the implementation of more environmentally friendly and efficient solutions, in line with global efforts to reduce carbon emissions and promote sustainable urban development;
- Research perspectives are recommended to focus on intelligent planning tools that enable optimal use of clean energy, assess classified thresholds for various species to control the effects of exposure, and explore the potential effect of EMF exposure related to the disruption of the intrinsic electrical activity of living organisms.

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Conflicts of Interest: The author declares no conflicts of interest.

References

[1] Suryavanshi, S.; Ghanegaonkar, P.; Kawade, R. *Insights into Retrofitting Internal Combustion Engine Vehicles to Battery Electric Vehicles for Eco-friendly Vehicle Technology*; SAE Technical Paper Series; SAE International: Warrendale, PA, USA, 2025. doi:10.4271/2025-01-5009.

[2] Delie, J.; Biedenweg, K.; Cerveny, L.K. Co-Occurrence of Landscape Values and Activities in Three Protected Areas. *J. Parks* **2026**, *1*, 3. doi:10.3390/jop1010003.

[3] Jin, F.; Feng, Y.; Zhang, Z.; Wang, Q.; Sun, Y. Simulation and Optimization of Urban Multiscale Ecological Networks Integrating Human Demand and Natural Processes. *Appl. Sci.* **2026**, *16*, 1431. doi:10.3390/app16031431.

[4] Benis, A.; Tamburis, O.; Chronaki, C.; Moen, A. One Digital Health: A Unified Framework for Future Health Ecosystems. *J. Med. Internet Res.* **2021**, *23*(2), e22189. doi:10.2196/22189.

[5] Razek, A. One Health Ecological Approach to Sustainable Wireless Energy Transfer Aboard Electric Vehicles for Smart Cities. *Energies* **2024**, *17*, 4349. doi:10.3390/en17174349.

[6] Kellaway, P. The part played by electric fish in the early history of bioelectricity and electrotherapy. *Bull. Hist. Med.* **1946**, *20*(2), 112–137. Available Online: https://pubmed.ncbi.nlm.nih.gov/20277440/.

[7] Razek, A. Potential biological effects on living tissues of biodiversity subsequent to exposure to high-frequency electromagnetic fields. *Therm. Sci. Eng.* **2025**, *8*(2), 11750. doi:10.24294/tse11750.

[8] Liu, Z.; Li, T.; Li, S.; Mi, C.C. Advancements and challenges in wireless power transfer: A comprehensive review. *Nexus* **2024**, *1*, 100014. doi:10.1016/j.ynexs.2024.100014.

[9] Levitt, B.B.; Lai, H.C.; Manville, A.M., II; Scarato, T. Flora and fauna: How nonhuman species interact with natural and man-made EMF at ecosystem levels and public policy recommendations. *Front. Public Health* **2025**, *13*, 1693873. doi:10.3389/fpubh.2025.1693873.

[10] Elharti, C.; Hammen, L.; Bensetti, M.; Palessonga, D.; Pichon, L. Impact of Inductive Charging for Electric Vehicles on Pacemakers. *IEEE J. Wireless Power Technol.* **2026**, *1*,

0101012. doi:10.1109/JWPT.2026.3689461.
[11] Razek, A. Biological and medical disturbances due to exposure to fields emitted by electromagnetic energy devices—A review. *Energies* **2022**, *15*, 4455. doi:10.3390/en15124455.
[12] Razek, A. Thermal effects of electromagnetic origin from heating processes to biological disturbances due to field exposure—A review. *Therm. Sci. Eng.* **2023**, *6*, 20–33. doi:10.24294/tse.v6i1.1950.
[13] Kim, J.H.; Lee, J.-K.; Kim, H.-G.; Kim, K.-B.; Kim, H.R. Possible effects of radiofrequency electromagnetic field exposure on central nerve system. *Biomol. Ther.* **2019**, *27*, 265–275. doi:10.4062/biomolther.2018.152.
[14] Lv, Z.; Zhao, K.; Li, J.; Li, S.; Zhao, X.; Xu, A.; et al. Nonthermal radiofrequency radiation promotes hematopoietic stem and progenitor cells function by regulating Ca^{2+} efflux. *Stem Cell Res. Ther.* **2026**, *17*, 115. doi:10.1186/s13287-026-04937-2.
[15] U.S. Food & Drug Administration 2020. Review of Published Literature between 2008 and 2018 of Relevance to Radiofrequency Radiation and Cancer. Available Online: https://www.fda.gov/media/135043/download (accessed on 19 May 2026).
[16] Batool, S.; Bibi, A.; Frezza, F.; Mangini, F. Benefits and hazards of electromagnetic waves, telecommunication, physical and biomedical: A review. *Eur. Rev. Med. Pharmacol. Sci.* **2019**, *23*, 3121–3128. doi: 10.26355/eurrev_201904_17596.
[17] Reagan-Shaw, S.; Mukhtar, H.; Ahmad, N. Resveratrol Imparts Photoprotection of Normal Cells and Enhances the Efficacy of Radiation Therapy in Cancer Cells. *Photochem. Photobiol.* **2008**, *84*, 415–421. doi:10.1111/j.1751-1097.2007.00279.x.
[18] Ayesha, S.; Abideen, Z.; Haider, G.; Zulfiqar, F.; El-Keblawy, A.; Rasheed, A.; et al. Enhancing sustainable plant production and food security: Understanding the mechanisms and impacts of electromagnetic fields. *Plant Stress* **2023**, *9*, 100198. doi:10.1016/j.stress.2023.100198.
[19] Aguilar-Torres, D.; Jiménez-Ramírez, O.; Luque-Zuñiga, G.; Perdomo, F.A.; Vázquez-Medina, R. Enhancing Raphanus sativus seed germination through ultrasound pretreatment and an automated system. *Next Res.* **2026**, *9*, 101806. doi:10.1016/j.nexres.2026.101806.
[20] Morelli, C.; Maranzano, P.; Otto, P. Spatiotemporal clustering of GHGs emissions in Europe: Exploring the role of spatial component. *Spat. Stat.* **2026**, *73*, 100960. doi:10.1016/j.spasta.2026.100960.
[21] Yu, C.; Tan, J.; Cheng, Y.; Mi, X. Data analysis and preprocessing techniques for air quality prediction: A survey. *Stoch. Environ. Res. Risk Assess.* **2024**, *38*(6), 2095–2117. doi:10.1007/s00477-024-02693-4.
[22] Otto, P.; Fusta Moro, A.; Rodeschini, J.; Shaboviq, Q.; Ignaccolo, R.; Golini, N.; et al. Spatiotemporal modelling of $PM_{2.5}$ concentrations in Lombardy (Italy): A comparative study. *Environ. Ecol. Stat.* **2024**, *31*(2), 245–272. doi:10.1007/s10651-023-00589-0.
[23] Rowland, O.E. Comparative analysis of meteorological parameters and their relationship with NO_2, PM_{10}, $PM_{2.5}$ and O_3 concentrations at selected urban air quality monitoring stations in Krakow, Paris, and Milan. *Discov. Environ.* **2024**, *2*(1), 75. doi:10.1007/s44274-024-00060-2.
[24] Marongiu, A.; Collalto, A.G.; Distefano, G.G.; Angelinon, E. Application of machine learning to estimate ammonia atmospheric emissions and concentrations. *Air* **2024**, *2*(1), 38–60. doi:10.3390/air2010003.
[25] Marongiu, A.; Colombo, L.; Collalto, A.G. Dynamic emission inventory of ammonia in northern Italy by machine learning. *Air Qual. Atmos. Health* **2025**, *18*, 3793–3811. doi:10.1007/s11869-025-01779-4.
[26] Banja, M.; Crippa, M.; Guizzardi, D.; Muntean, M.; Pagani, F.; Pisoni, E. A comparative analysis of EDGAR and UNFCCC GHG emissions inventories: insights on trends, methodology and data discrepancies. *Earth Syst. Sci. Data* **2025**, *17*(11), 6461–6486. doi:10.5194/essd-17-6461-2025.
[27] Jang, J.M.; Kim, J.H.; Lee, J.; Hong, J.; Kim, D.W.; Kim, S.J. Gradient-structured MXene/ZIF/CNT hybrid films for largely enhanced electromagnetic absorption in EMI shielding. *Chem. Eng. J.* **2025**, *503*, 158691. doi:10.1016/j.cej.2024.158691.
[28] Kim, J.H. Radiation hormesis and reactive oxygen species-mediated stress priming in plants. *Plant Sci.* **2025**, *359*, 112602. doi:10.1016/j.plantsci.2025.112602.
[29] Prior, J.O.; Lecoq, P. Radiation-based medical imaging techniques: An overview. In *Handbook of Particle Detection and Imaging*; Fleck, I., Titov, M., Grupen, C., Buvat, I., Eds.; Springer: Cham, Switzerland, 2021. doi:10.1007/978-3-319-93785-4_35.
[30] Lane, S.A.; Slater, J.M.; Yang, G.Y. Image-Guided Proton Therapy: A Comprehensive Review. *Cancers* **2023**, *15*, 2555. doi:10.3390/cancers15092555.
[31] Lee, J.; Shin, N.Y.; Lee, S.J.; Cho, Y.J.; Jung, I.H.; Sung, J.W.; et al. Development of Magnetic Resonance-Compatible Head Immobilization Device and Initial Experience of Magnetic Resonance-Guided Radiation Therapy for Central Nervous System Tumors. *Pract. Radiat. Oncol.* **2024**, *14*, e324–e333. doi:10.1016/j.prro.2024.04.012.
[32] International Commission on Non-Ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric and magnetic fields for low frequencies (1 Hz–100 kHz). *Health Phys.* **2010**, *99*, 818–836. Available Online: https://icnirp.org/cms/upload/publications/ICNIRPLFgdl.pdf.
[33] International Commission on Non-Ionizing Radiation Protection. Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). *Health Phys.* **2020**, *118*, 483–524. Available Online: https://www.icnirp.org/cms/upload/publications/ICNIRPrfgdl2020.pdf.
[34] *IEEE Standard C95.1-2019*; IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz. IEEE Standards Association: Piscataway, NJ, USA, 2019. doi:10.1109/IEEESTD.2019.8859679.
[35] Ramos, V.; Suarez, O.J.; Febles-Santana, V.M.; Suarez-Rodriguez, D.S.; Aguirre, E.; De-Miguel-Bilbao, S.; et al. Electromagnetic Characterization of UHF-RFID Fixed Reader in Healthcare Centers Related to the Personal and Labor Health. *IEEE Access* **2022**, *10*, 28614–28630. doi:10.1109/ACCESS.2022.3156477.
[36] Wust, P.; Kortüm, B.; Strauss, U.; Nadobny, J.; Zschaeck, S.; Beck, M.; et al. Non-Thermal Effects of Radiofrequency Electromagnetic Fields. *Sci. Rep.* **2020**, *10*, 13488. doi:10.1038/s41598-020-69561-3.
[37] Zradziński, P.; Karpowicz, J.; Gryz, K. Electromagnetic Energy Absorption in a Head Approaching a Radiofrequency Identification (RFID) Reader Operating at 13.56 MHz in Users of Hearing Implants Versus Non-Users. *Sensors* **2019**, *19*, 3724. doi:10.3390/s19173724.
[38] Jalilian, H.; Eeftens, M.; Ziaei, M.; Röösli, M. Public Exposure to Radiofrequency Electromagnetic Fields in Everyday Microenvironments: An Updated Systematic Review for Europe. *Environ. Res.* **2019**, *176*, 108517. doi:10.1016/j.envres.2019.05.048.
[39] Leach, V.; Weller, S.; Redmayne, M. A Novel Database of Bio-Effects from Non-Ionizing Radiation. *Rev. Environ. Health* **2018**, *33*, 273–280. doi:10.1515/reveh-2018-0017.
[40] Razek, A. Assessment and Categorization of Biological

Effects and Atypical Symptoms Owing to Exposure to RF Fields from Wireless Energy Devices. *Appl. Sci.* **2023**, *13*, 1265. doi:10.3390/app13031265.

[41] Huang, P.C.; Cheng, M.T.; Guo, H.R. Representative Survey on Idiopathic Environmental Intolerance Attributed to Electromagnetic Fields in Taiwan and Comparison with the International Literature. *Environ. Health* **2018**, *17*, 5. doi:10.1186/s12940-018-0351-8.

[42] Baliatsas, C.; Van Kamp, I.; Lebret, E.; Rubin, G.J. Idiopathic Environmental Intolerance Attributed to Electromagnetic Fields (IEI-EMF): A Systematic Review of Identifying Criteria. *BMC Public Health* **2012**, *12*, 643. doi:10.1186/1471-2458-12-643.

[43] Huang, P.C.; Chiang, J.C.; Cheng, Y.Y.; Cheng, T.-J.; Huang, C.-Y.; Chuang, Y.-T.; et al. Physiological Changes and Symptoms Associated with Short-Term Exposure to Electromagnetic Fields: A Randomized Crossover Provocation Study. *Environ. Health* **2022**, *21*, 31. doi:10.1186/s12940-022-00843-1.

[44] Genuis, S.J.; Lipp, C.T. Electromagnetic Hypersensitivity: Fact or fiction? *Sci. Total Environ.* **2012**, *414*, 103–112. doi:10.1016/j.scitotenv.2011.11.008.

[45] Barth, A.; Ponocny, I.; Gnambs, T.; Winker, R. No Effects of Short-Term Exposure to Mobile Phone Electromagnetic Fields on Human Cognitive Performance: A Meta-Analysis. *Bioelectromagnetics* **2012**, *33*, 159–165. doi:10.1002/bem.20697.

[46] Curcio, G. Exposure to Mobile Phone-Emitted Electromagnetic Fields and Human Attention: No Evidence of a Causal Relationship. *Front. Public Health* **2018**, *6*, 42. doi:10.3389/fpubh.2018.00042.

[47] Pophof, B.; Kuhne, J.; Schmid, G.; Weiser, E.; Dorn, H.; Henschenmacher, B.; et al. The effect of exposure to radiofrequency electromagnetic fields on cognitive performance in human experimental studies: Systematic review and meta-analyses. *Environ. Int.* **2024**, *191*, 108899. doi:10.1016/j.envint.2024.108899.

[48] Sunstein, C.R. Beyond the Precautionary Principle. *Univ. Pa. Law Rev.* **2003**, *151*(3), 1003–1058. doi:10.2307/3312884.

[49] Liu, E.; Cai, Z.; Ye, Y.; Zhou, M.; Liao, H.; Yi, Y. An Overview of Flexible Sensors: Development, Application, and Challenges. *Sensors* **2023**, *23*, 817. doi:10.3390/s23020817.

[50] Devi, D.H.; Duraisamy, K.; Armghan, A.; Alsharari, M.; Aliqab, K.; Sorathiya, V.; et al. 5G Technology in Healthcare and Wearable Devices: A Review. *Sensors* **2023**, *23,* 2519. doi:10.3390/s23052519.

[51] Chakrabarti, S.; Biswas, N.; Jones, L.D.; Kesari, S.; Ashili, S. Smart Consumer Wearables as Digital Diagnostic Tools: A Review. *Diagnostics* **2022**, *12*, 2110. doi:10.3390/diagnostics12092110.

[52] Escobar-Linero, E.; Muñoz-Saavedra, L.; Luna-Perejón, F.; Sevillano, J.L.; Domínguez-Morales, M. Wearable Health Devices for Diagnosis Support: Evolution and Future Tendencies. *Sensors* **2023**, *23*, 1678. doi:10.3390/s23031678.

[53] Ahmed, M.R.; Newby, S.; Potluri, P.; Mirihanage, W.; Fernando, A. Emerging Paradigms in Fetal Heart Rate Monitoring: Evaluating the Efficacy and Application of Innovative Textile-Based Wearables. *Sensors* **2024**, *24,* 6066. doi:10.3390/s24186066.

[54] Moon, K.S.; Lee, S.Q. A Wearable Multimodal Wireless Sensing System for Respiratory Monitoring and Analysis. *Sensors* **2023**, *23*, 6790. doi:10.3390/s23156790.

[55] Khan Mamun, M.M.R.; Sherif, A. Advancement in the Cuffless and Noninvasive Measurement of Blood Pressure: A Review of the Literature and Open Challenges. *Bioengineering* **2023**, *10,* 27. doi:10.3390/bioengineering10010027.

[56] Xing, Y.; Yang, K.; Lu, A.; Mackie, K.; Guo, F. Sensors and Devices Guided by Artificial Intelligence for Personalized Pain Medicine. *Cyborg Bionic Syst.* **2024**, *13*, 0160. doi:10.34133/cbsystems.0160.

[57] Bhuva, A.N.; Moralee, R.; Brunker, T.; Lascelles, K.; Cash, L.; Patel, K.P.; et al. Evidence to support magnetic resonance conditional labelling of all pacemaker and defibrillator leads in patients with cardiac implantable electronic devices. *Eur. Heart J.* **2022**, *43*, 2469–2478. doi:10.1093/eurheartj/ehab350.

[58] Joo, H.; Lee, Y.; Kim, J.; Yoo, J.S.; Yoo, S.; Kim, S.; et al. Soft Implantable Drug Delivery Device Integrated Wirelessly with Wearable Devices to Treat Fatal Seizures. *Sci. Adv.* **2021**, *7*, eabd4639. doi:10.1126/sciadv.abd4639.

[59] Cheng, Y.; Xie, D.; Han, Y.; Guo, S.; Sun, Z.; Jing, L.; et al. Precise management system for chronic intractable pain patients implanted with spinal cord stimulation based on a remote programming platform: Study protocol for a randomized controlled trial (PreMaSy study). *Trials* **2023**, *24*, 580. doi:10.1186/s13063-023-07595-4.

[60] Gordon, J.S.; Maynes, E.J.; O'Malley, T.J.; Pavri, B.B.; Tchantchaleishvili, V. Electromagnetic interference between implantable cardiac devices and continuous-flow left ventricular assist devices: A review. *J. Interv. Card. Electrophysiol.* **2021**, *61*, 1–10. doi:10.1007/s10840-020-00930-8.

[61] Liu, D.; Li, G.; Wang, S.; Liu, Z.; Wang, Y.; Connolly, L.; et al. A magnetic resonance conditional robot for lumbar spinal injection: Development and preliminary validation. *Int. J. Med. Robot.* **2024**, *20*, e2618. doi:10.1002/rcs.2618.

[62] Martinez-Hernandez, U.; Metcalfe, B.; Assaf, T.; Jabban, L.; Male, J.; Zhang, D. Wearable Assistive Robotics: A Perspective on Current Challenges and Future Trends. *Sensors* **2021**, *21*, 6751. doi:10.3390/s21206751.

[63] Li, Y.; Luo, S.; Luo, R.; Liu, H. A novel real-time assistive hip-wearable exoskeleton robot based on motion prediction for lower extremity rehabilitation in subacute stroke: A single-blinded, randomized controlled trial. *BMC Neurol.* **2025**, *25*, 399. doi:10.1186/s12883-025-04437-5.

[64] Winterbottom, L.; Chen, A.; Mendonca, R.; Nilsen, D.M.; Ciocarlie, M.; Stein, J. Clinician perceptions of a novel wearable robotic hand orthosis for post-stroke hemiparesis. *Disabil. Rehabil.* **2025**, *47*, 1577–1586. Available Online: https://avachen.net/pdfs/Winterbottom_Chen_PerceptionsRoboticHandOrthosisStroke.pdf.

[65] Kranold, L.; Xi, J.; Goren, T.; Kuster, N. Dosimetric Electromagnetic Safety of People with Implants: A Neglected Population? *Bioelectromagnetics* **2025**, *46*, e70023. doi:10.1002/bem.70023.

[66] Hammen, L.; Pichon, L.; Le Bihan, Y.; Bensetti, M.; Fleury, G. Testing immunity of active implantable medical devices to industrial magnetic field environments. In Proceedings of the International Symposium and Exhibition on Electromagnetic Compatibility—EMC Europe, Göteborg, Sweden, 5–8 September 2022.

[67] Hammen, L. Electromagnetic Compatibility of Active Implantable Medical Devices at the Workplace: The Case of Pacemakers. Ph.D. Thesis, Université Paris-Saclay, Orsay, France, 2024. Available Online: https://theses.hal.science/tel-04971996/document (accessed on 21 December 2025).

[68] Razek, A. Assessment of a Functional Electromagnetic Compatibility Analysis of Near-Body Medical Devices Subject to Electromagnetic Field Perturbation. *Electronics* **2023**, *12*, 4780. doi:10.3390/electronics12234780.

[69] Miguel-Tomé, S.; Llinás, R.R. Broadening the definition of a nervous system to better understand the evolution of plants and animals. *Plant Signal. Behav.* **2021**, *16*(10), e1927562.

doi:10.1080/15592324.2021.1927562.

[70] Bhatla, S.C.; Lal, M.A. Plant Movements. In *Plant Physiology, Development and Metabolism*; Springer: Singapore, 2023; pp. 641–659. doi:10.1007/978-981-99-5736-1_29.

[71] Grinberg, M.A.; Il'in, N.V.; Nemtsova, Y.A.; Dolinin, A.A.; Ivanova, A.V.; Sarafanov, F.G.; et al. Effect of Increased Ionizing Radiation and Near-Null Magnetic Field on Electrical Signals of Plants. *Radiophys. Quantum Electron.* **2025**, *67*, 788–798. doi:10.1007/s11141-025-10418-y.

[72] Kozlova, E.; Yudina, L.; Sukhova, E.; Sukhov, V. Analysis of Electrome as a Tool for Plant Monitoring: Progress and Perspectives. *Plants* **2025**, *14*, 1500. doi:10.3390/plants14101500.

[73] Zarrin Ghalami, R.; Duszyn, M.; Karpiński, S. Absorption of Energy in Excess, Photoinhibition, Transpiration, and Foliar Heat Emission Feedback Loops During Global Warming. *Cells* **2026**, *15*, 75. doi:10.3390/cells15010075.

[74] Szechyńska-Hebda, M.; Lewandowska, M.; Witoń, D.; Fichman, Y.; Mittler, R.; Karpiński, S.M. Aboveground plant-to-plant electrical signaling mediates network acquired acclimation. *Plant Cell* **2022**, *34*(8), 3047–3065. doi:10.1093/plcell/koac150.

[75] Stolarz, M. Integration of Plant Electrophysiology and Time-Lapse Video Analysis via Artificial Intelligence for the Advancement of Precision Agriculture. *Sustainability* **2025**, *17*, 5614. doi:10.3390/su17125614.

[76] Xia, A.; Wu, Y.; Zhai, K.; Xiang, D.; Li, L.; Qin, Z.; et al. Plant Electrophysiological Parameters Represent Leaf Intracellular Water-Nutrient Metabolism and Immunoregulations in *Brassica rapa* During *Plasmodiophora* Infection. *Plants* **2025**, *14*(15), 2337. doi:10.3390/plants14152337.

[77] Bertagna, F.; Ahmad, S.; Lewis, R.; Silva, S.R.P.; McFadden, J.; Huang, C.L.H.; et al. Electromagnetic fields modulate neuronal membrane ionic currents through altered cellular calcium homeostasis. *Ann. N. Y. Acad. Sci.* **2025**, *1550*, 273–282. doi:10.1111/nyas.15386.

[78] Sanan-Mishra, N. Electric signaling and long-distance communication in plants. In *Sensory Biology of Plants*; Sopory, S., Ed.; Springer: Singapore, 2019. doi:10.1007/978-981-13-8922-1_19.

[79] Khan, I.; Sohail; Zaman, S.; Li, G.; Fu, M. Adaptive responses of plants to light stress: mechanisms of photoprotection and acclimation. A review. *Front. Plant Sci.* **2025**, *16*, 1550125. doi:10.3389/fpls.2025.1550125.

[80] Xu, Y.; Kaste, J.A.M.; Weise, S.E.; Shachar-Hill, Y.; Sharkey, T.D. The effects of photosynthetic rate on respiration in light, starch/sucrose partitioning, and other metabolic fluxes within photosynthesis. *Sci. Rep.* **2025**, *15*, 8389. doi:10.1038/s41598-025-88574-4.

[81] Levitt, B.B.; Lai, H.C.; Manville, A.M., II. Low-level EMF effects on wildlife and plants: What research tells us about an ecosystem approach? *Front. Public Health* **2022**, *10*, 1000840. doi:10.3389/fpubh.2022.1000840.

[82] Maxwell, J.C. A dynamical theory of the electromagnetic field. *Phil. Trans. R. Soc. Lond.* **1865**, *155*, 459–512. doi:10.1098/rstl.1865.0008.

[83] Pennes, H.H. Analysis of tissue and arterial blood temperatures in the resting human forearm. *J. Appl. Physiol.* **1998**, *85*(1) 5–34. doi:10.1152/jappl.1998.85.1.5.

[84] Antunes, O.J.; Bastos, J.P.A.; Sadowski, N.; Razek, A.; Santandrea, L.; Bouillault, F.; et al. Comparison between nonconforming movement methods. *IEEE Trans. Magn.* **2006**, *42*, 599–602. doi:10.1109/TMAG.2006.871431.

[85] Carpes, W.P., Jr.; Pichon, L.; Razek, A. A 3D finite element method for the modelling of bounded and unbounded electromagnetic problems in the time domain. *Int. J. Numer. Model.* **2000**, *13*, 527–540. doi: 10.1002/1099-1204(200011/12)13:6<527::AID-JNM391>3.0.CO;2-V.

[86] Shanmugam, Y.; Narayanamoorthi, R.; Vishnuram, P.; Bajaj, M.; AboRas, K.M.; Thakur, P. A systematic review of dynamic wireless charging system for electric transportation. *IEEE Access* **2022**, *10*, 133617–133642. doi:10.1109/ACCESS.2022.3227217.

[87] Ibrahim, M. Wireless Inductive Charging for Electrical Vehicles: Electromagnetic Modelling and Interoperability Analysis. Ph.D. Thesis, University of Paris-Sud, Orsay, France, 2014. Available Online: https://theses.hal.science/tel-01127163/file/2014PA112369.pdf (accessed on 27 May 2026).

[88] Razek, A. Sustainable Management of Energy Storage in Electric Vehicles Involved in a Smart Urban Environment. *Energy Storage Appl.* **2025**, *2*, 7. doi:10.3390/esa2020007.

[89] José, R.; Rodrigues, H. A Review on Key Innovation Challenges for Smart City Initiatives. *Smart Cities* **2024**, *7*, 141–162. doi:10.3390/smartcities7010006.

[90] Razek, A. Sustainable Management of Energy, Storage, and Wireless Transfer in Electric Vehicles Operating in an Ecological Environment. *Transp. Dev. Res.* **2026**, *4*(1), 78–89. doi:10.55121/tdr.v4i1.1185.

[91] Wen, H.; Zhou, X.; Guo, M.; Wen, J.; Zhang, K.; Yan, Z.; et al. A Strong Misalignment Tolerance and Low Stray Magnetic Fields Wireless Power Transfer System for Planar Type AUV with Hybrid Magnetic Coupler. *IEEE Trans. Power Electron.* **2026**, *41*(10), 18672–18684. doi:10.1109/TPEL.2026.3692497.

[92] Wang, F.; Yang, Q.; Zhang, X.; Yuan, Z.; Chen, T.; Hu, A.P.; et al. A Tri-SS Hybrid Wireless Power Transfer System Achieving High Power Density and Misalignment Tolerance. *IEEE Trans. Power Electron.* **2026**, *41*(2), 2958–2974. doi:10.1109/TPEL.2025.3606409.

[93] Ding, P.; Bernard, L.; Pichon, L.; Razek, A. Evaluation of Electromagnetic Fields in Human Body Exposed to Wireless Inductive Charging System. *IEEE Trans. Magn.* **2014**, *50*, 1037–1040. doi:10.1109/TMAG.2013.2284245.

[94] Makarov, S.N.; Noetscher, G.M.; Yanamadala, J.; Piazza, M.W.; Louie, S.; Prokop, A.; et al. Virtual Human Models for Electromagnetic Studies and Their Applications. *IEEE Rev. Biomed. Eng.* **2017**, *10*, 95–121. doi:10.1109/RBME.2017.2722420.

[95] Peng, Z.; Gao, N.; Wu, B.; Chen, Z.; Xu, X.G. A Review of Computational Phantoms for Quality Assurance in Radiology and Radiotherapy in the Deep-Learning Era. *J. Radiat. Prot. Res.* **2022**, *47*, 111–133. doi:10.14407/jrpr.2021.00402.

[96] Razek, A. Digital Monitoring of Electromagnetic Radiation Associated with Biodiversity (One Health) in Natural Parks: A Narrative Review. *J. Plant Electrobiol.* **2026**, *1*(2), 94–107. doi:10.62762/JPE.2026.885819.

[97] Xie, R.; Wu, J.; Chen, Y.; Chen, X.; Yi, Y.; Zhang, Y. Wireless Charging System Based on Dynamic Phase-Shift Controlled Dual-Transmitting Coils and Its Misalignment Tolerance Mechanism. *IEEE Trans. Ind. Electron.* **2026**, *73*(6), 9534–9539. doi:10.1109/TIE.2025.3649870.

[98] Islamov, I. Development and Electromagnetic Compatibility of Smart Antenna Systems for 5G. In *Smart Antenna Systems for 5G, Radar, Navigation and Satellite Technologies*; Springer: Cham, Switzerland, 2026. doi:10.1007/978-3-032-15489-7_3.

[99] Liu, Z.; Wang, H.; He, S.; Wang, X. Failure phenomenon of electromagnetic shielding clothing on human health protection in electromagnetic radiation environment. *J. Text. Inst.* **2022**, *114*, 811–819. doi:10.1080/00405000.2022.2089832.

[100] Panyaram, S. Integrating Artificial Intelligence with Big Data for Real-Time Insights and Decision-Making in Complex Systems. *FMDB Trans. Sustain. Intell. Netw.* **2024**, *1*(2), 85–95. doi:10.69888/FTSIN.2024.000211.

[101] Deliu, D.; Olariu, A. The Role of Artificial Intelligence and Big Data Analytics in Shaping the Future of Professions in Industry 6.0: Perspectives from an Emerging Market. *Electronics* **2024**, *13*, 4983. doi:10.3390/electronics13244983.

[102] Parmar, A. AI-driven data analytics for real-time decision-making. *Int. J. Prog. Res. Eng. Manag. Sci.* **2025**, *5*(5), 372–386. doi:10.58257/IJPREMS40153.

[103] Chow, J.C.L. Quantum Computing and Machine Learning in Medical Decision-Making: A Comprehensive Review. *Algorithms* **2025**, *18*, 156. doi:10.3390/a18030156.

[104] Grieves, M.; Vickers, J. Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In *Trans-disciplinary Perspectives on Complex Systems*; Springer: Cham, Switzerland, 2017; pp. 85–113. doi:10.1007/978-3-319-38756-7_4.

[105] Tao, F.; Sui, F.; Liu, A.; Qi, Q.; Zhang, M.; Song, B.; et al. Digital twin-driven product design framework. *Int. J. Prod. Res.* **2019**, *57*, 3935–3953. doi:10.1080/00207543.2018.1443229.

[106] Sun, T.; He, X.; Li, Z. Digital twin in healthcare: Recent updates and challenges. *Digit. Health* **2023**, *9*, 20552076221149651. doi:10.1177/20552076221149651.

[107] Asciak, L.; Kyeremeh, J.; Luo, X.; Kazakidi, A.; Connolly, P.; Picard, F.; et al. Digital twin assisted surgery, concept, opportunities, and challenges. *npj Digit. Med.* **2025**, *8*, 32. doi:10.1038/s41746-024-01413-0.

[108] Lin, J.C. The WHO-Commissioned Systematic Reviews on Health Effects of Microwave and RF Radiation [Health Matters]. *IEEE Microw. Mag.* **2026**, *27*(3), 14–17. doi:10.1109/MMM.2025.3637921.

[109] Vermeeren, G.; Debaillie, B.; Kühn, S.; Torfs, G.; Kuster, N.; Demeester, P.; et al. Experimental and numerical assessment of near-field exposure of a 60 GHZ communication antenna. *Radiat. Prot. Dosim.* **2026**, *202*(8), 638–644. doi:10.1093/rpd/ncag007.

[110] Dikmen, I.C. Continuous Monitoring and Modeling of High-Frequency EM Pollution Using Cutting-Edge Regression Techniques. *IEEE Access* **2025**, *13*, 46627–46637. doi:10.1109/ACCESS.2025.3548841.

[111] Aslan, C.A.; Korunur Engiz, B.; Kurnaz, C.; Cheema, A.A.; Karadag, T. In Situ Assessment of EMF Exposure across Urban Districts of Samsun, Türkiye. *Electronics* **2026**, *15*, 68. doi:10.3390/electronics15010068.

[112] Manville, A.M., II; Levitt, B.B.; Lai, H.C. Health and environmental effects to wildlife from radio telemetry and tracking devices—State of the science and best management practices. *Front. Vet. Sci.* **2024**, *11*, 1283709. doi:10.3389/fvets.2024.1283709.

[113] Ascona García, P.P.; Ordoñez Carpio, G.E.; Zelada Zamora, W.M.; Villanueva Pedraza, E.; Fernandez Villarroel, R.A. Magnetic Field Penetration Depth in Various Materials and Applications. *Appl. Sci.* **2025**, *15*, 2225. doi:10.3390/app15042225.

[114] Mohammed, H.S. Effects of wireless communication electromagnetic fields on human and animal brain activity. In *Electromagnetic Fields of Wireless Communications: Biological and Health Effects*; Panagopoulos, D.J., Ed.; CRC Press: Boca Raton, FL, USA, 2022.

[115] Roux, D.; Vian, A.; Girard, S.; Bonnet, P.; Paladian, F.; Davies, E.; et al. Electromagnetic fields (900MHz) evoke consistent molecular responses in tomato plants. *Physiol. Plant.* **2006**, *128*, 283–288. doi:10.1111/j.1399-3054.2006.00740.x.

[116] Phillips, J.L.; Singh, N.P.; Lai, H. Electromagnetic fields and DNA damage. *Pathophysiology* **2009**, *16*, 79–88. doi:10.1016/j.pathophys.2008.11.005.

[117] Yakymenko, I.; Tsybulin, O.; Sidorik, E.; Henshel, D.; Kyrylenko, O.; Kyrylenko, S. Oxidative mechanisms of biological activity of low-intensity radiofrequency radiation. *Electromagn. Biol. Med.* **2016**, *35*, 186–202. doi:10.3109/15368378.2015.1043557.

[118] Yakymenko, I.; Tsybulin, O. Oxidative stress induced by wireless communication electromagnetic fields. In *Electromagnetic Fields of Wireless Communications: Biological and Health Effects*; Panagopoulos, D.J., Ed.; CRC Press: Boca Raton, FL, USA, 2022.

[119] Jagetia, G.C. Genotoxic effects of wireless communication electromagnetic fields. In *Electromagnetic Fields of Wireless Communications: Biological and Health Effects*; Panagopoulos, D.J., Ed.; CRC Press: Boca Raton, FL, USA, 2022.

[120] Miller, K.; Harrison, K.; Martin, J.H.; Nixon, B.; De Iuliis, G.N. The impacts of wireless communication electromagnetic fields on human reproductive biology. In *Electromagnetic Fields of Wireless Communications: Biological and Health Effects*; Panagopoulos, D.J., Ed.; CRC Press: Boca Raton, FL, USA, 2022.

[121] Cappucci, U.; Casale, A.M.; Proietti, M.; Marinelli, F.; Giuliani, L.; Piacentini, L. WiFi related radiofrequency electromagnetic fields promote transposable element dysregulation and genomic instability in *Drosophila melanogaster*. *Cells* **2022**, *11*, 4036. doi:10.3390/cells11244036.

[122] Choi, J.; Min, K.; Jeon, S.; Kim, N.; Pack, J.K.; Song, K. Continuous exposure to 1.7 GHz LTE electromagnetic fields increases intracellular reactive oxygen species to decrease human cell proliferation and induce senescence. *Sci. Rep.* **2020**, *10*, 9238. doi:10.1038/s41598-020-65732-4.

[123] Kim, J.H.; Jeon, S.; Choi, H.D.; Lee, J.H.; Bae, J.S.; Kim, N.; et al. Exposure to long-term evolution radiofrequency electromagnetic fields decreases neuroblastoma cell proliferation via Akt/mTOR-mediated cellular senescence. *J. Toxicol. Environ. Health A* **2021**, *84*, 846–857. doi:10.1080/15287394.2021.1944944.

[124] Shahin, S.; Singh, V.P.; Shukla, R.K.; Dhawan, A.; Gangwar, R.K.; Singh, S.P.; et al. 2.45 GHz microwave irradiation-induced oxidative stress affects implantation or pregnancy in mice, *Mus musculus*. *Appl. Biochem. Biotechnol.* **2013**, *169*, 1727–1751. doi:10.1007/s12010-012-0079-9.

[125] Czerwiński, M.; Vian, A.; Woodcock, B.A.; Goliński, P.; Virto, L.R.; Januszkiewicz, Ł. Do electromagnetic fields used in telecommunications affect wild plant species? A control impact study conducted in the field. *Ecol. Indic.* **2023**, *150*, 110267. doi:10.1016/j.ecolind.2023.110267.

[126] Deena, K.; Maadurshni, G.B.; Manivannan, J.; Sivasamy, R. Short-term exposure of 2.4 GHz electromagnetic radiation on cellular ROS generation and apoptosis in SH-SY5Y cell line and impact on developing chick embryo brain tissue. *Mol. Biol. Rep.* **2025**, *52*, 144. doi:10.1007/s11033-025-10217-8.

[127] Özen, G.; Kahvecioğlu, D.; Bulut, İ.; Erel, Ö.; Neşelioğlu, S.; Üstün, Y.; et al. Effect of Mobile phone usage during pregnancy on total oxidant and antioxidant levels in cord blood. *J. Dr. Behcet Uz Child. Hosp.* **2023**, *13*, 177–184. doi:10.4274/jbuch.galenos.2023.70845.

[128] IEA—International Energy Agency. *Global EV Outlook 2024: Moving Towards Increased Affordability*; IEA: Paris, France, 2024. Available Online: https://iea.blob.core.windows.net/assets/a9e3544b-0b12-4e15-b407-65f5c8ce1b5f/GlobalEVOutlook2024.pdf.

Licence: CC BY 4.0.
[129] IEA—International Energy Agency. *Global EV Outlook 2023: Catching up with Climate Ambitions*; IEA: Paris, France, 2023. Available Online: https://www.iea.org/reports/global-ev-outlook-2023. Licence: CC BY 4.0.
[130] Zaino, R.; Ahmed, V.; Alhammadi, A.M.; Alghoush, M. Electric Vehicle Adoption: A Comprehensive Systematic Review of Technological, Environmental, Organizational and Policy Impacts. *World Electr. Veh. J.* **2024**, *15*, 375. doi:10.3390/wevj15080375.
[131] Brzozek, C.; Mate, R.; Bhatt, C.R.; Loughran, S.; Wood, A.W.; Karipidis, K. Investigating the impact of anthropogenic radiofrequency electromagnetic fields on animals and plants in the environment: analysis from a systematic map. *Int. J. Environ. Stud.* **2024**, *81*(5), 2343–2358. doi:10.1080/00207233.2024.2375861.
[132] Zambrano-de la Torre, M.; Guzman-Alfaro, S.; Guzmán-Fernández, M.; Robles-Ortiz, R.; Espino-Salinas, C.H.; Sánchez-Reyna, A.G. Electrophysiological Characterization of *Aloe vera* Under Abiotic Stress: A Quantitative Basis for Plant-Based Biodosimetry. *Appl. Sci.* **2026**, *16*, 2523. doi:10.3390/app16052523.
[133] Barbosa-Caro, J.C.; Wudick, M.M. Revisiting plant electric signaling: Challenging an old phenomenon with novel discoveries. *Curr. Opin. Plant Biol.* **2024**, *79*, 102528. doi:10.1016/j.pbi.2024.102528.
[134] Sai, K.; Sood, N.; Saini, I. Abiotic Stress Classification through Spectral Analysis of Enhanced Electrophysiological Signals of Plants. *Biosyst. Eng.* **2022**, *219*, 189–204. doi:10.1016/j.biosystemseng.2022.04.025.
[135] Lysov, M.; Maximova, I.; Vasiliev, E.; Getmanskaya, A.; Turlapov, V. Entropy as a High-Level Feature for XAI-Based Early Plant Stress Detection. *Entropy* **2022**, *24*, 1597. doi:10.3390/e24111597.



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