SCIENTIFIC Publishing Limited

Digital Technologies Research and Applications
http://ojs.ukscip.com/index.php/dtra

Review

Analysis of the Interaction Effects of Electromagnetic Fields with Major Living Tissues—One Health Concept Numerical Evaluation Strategy

Adel Razek *

Group of Electrical Engineering—Paris (GeePs), CNRS, University of Paris-Saclay and Sorbonne University, F91190 Gif sur Yvette, France
* Correspondance: adel.razek@centralesupelec.fr

Received: 28 March 2024; **Revised:** 18 April 2024; **Accepted**: 30 April 2024; **Published**: 11 May 2024

Abstract: The well-being and sociability of individuals have always been part of modernity. The development of new technologies that meet these aspirations is receiving increasing attention. Thus, strengthening the desired objectives of these technologies and minimizing their undesirable side effects is the subject of growing commitment. The present contribution aims, in this context, to evaluate and analyze the desired and undesirable effects of the interaction of electromagnetic fields with living tissues in general. These are routines based on mathematical modeling reinforcing the expected functions as well as those of control and protection against undesirable effects. These adverse effects correspond to the "One Health" concept, which encompasses the health of animals, plants and humans, as well as ecological disorders created by human activity. First, in this article, the interactions of electromagnetic fields with tissues are analyzed, involving their thermal biological effects of desired and undesired exposures. The roles of blood and sap fluids in bio-affected tissues are then analyzed. Secondly, the equations governing electromagnetics and bio-heat, as well as their coupled solution are studied. Third, the thermal behavior of tissues and the adverse effects of exposure are examined. Next, monitoring and defending the effects of exposures are discussed. This contribution, supported by a review of the literature, illustrates routines for mathematical modeling of the generalized interaction of electromagnetic fields with living tissues.

Keywords: electromagnetic field; living tissues; thermal effects; blood and sap; bio-heat; mathematical models; One Health

1. Introduction

Throughout human history, the quest for modernity has never stopped. Nowadays, many daily processes and devices are part of modern human society. The association of these auxiliaries with humans leads, in addition to the desired purposes, to undesirable effects. These side effects can affect not only humans, but also wildlife and other objects. This is due to the proximity of humans' environments to those of others. It should be noted that humans, fauna, and flora interact regularly. Each of them needs and helps others, for example; the first can feed others and needs to be fed by them. In addition, an activity necessary for any can interact positively or negatively with oneself or with others. This thus corroborates the "One Health" concept, which includes the health of animals, plants and humans, as well as environmental disturbances generated by human activity [1]. Moreover, an external phenomenon can interact in the same way with any of them. Regardless, the effects of such exposures may be desired by some but undesirable by others.

https://doi.org/10.54963/dtra.v3i2.243

One of the existing environmental issues today is linked to exposure to electromagnetic fields (EMFs). These exhibit large frequency spread including non-ionizing (10^3–10^{14} Hz) and ionizing (10^{15}–10^{22} Hz) ranges, see Figure 1a. The ionizing radiation is likely to have adverse health effects by generating molecular disturbances leading to tissue damage. The non-ionizing fields are used in the daily activities of humans for communications, information transfer, process supervision, food preparation, industrial processing, health care, etc. The connections between EMFs and humans in these activities certainly play an important role in human well-being. In addition to these desired dealings, there are undesirable effects on human tissues as well as those of fauna and flora [2–15]. These EMF exposures are due to two types of sources, near field (NF) as telephone cells [9], and far field (FF) as antenna towers for telephone cells [7,8]. These two types of exposure can produce biological effects (BEs) on the various exposed tissues of humans, fauna and flora. These BEs are related to induced fields in tissues and generally result in thermal effects (in the range of 100 kHz up to 300 GHz), see Figure 1b, depending on the characteristics of the EMF source, the features of the exposed material, and the conditions and duration of exposure [9,10]. The higher the field strength and frequency are in the tissue and the longer the exposure interval, the greater the temperature rise will be. Such BEs can be desired in healthcare hyperthermia treatments or microwave cooking [10]. Otherwise, BEs due to unwanted exposures are generally harmful and need to be supervised. Excessive induced EMFs or heating in tissues would cause an alteration in the molecular behavior of tissues, which denotes non-thermal BEs. These latter effects can cause tissue damage.

The governing equations involved in determining the distribution of temperature rise in tissues consist of the EMF equations coupled, via the dissipated electric power distribution, to the tissue heat transfer equations. These are the bio heat (BH) equations in irrigated tissues. The blood fluids of humans and fauna generally irrigate them as well as the sap fluids of flora in general [16].

Thresholds are established to control tissue security, relative to induced EMF values and their thermal BEs. These are denoted by the specific absorption rate (SAR) and temperature rise ΔT. The 3D distributions of these quantities obtained from the coupled solution of the EMF and the BH equations should be checked with thresholds to ensure the tissue's security [9,10,17]. These thresholds depend on, the tissue part of the body or plant, the relation with the exposure source, and the exposure conditions. Concerning tissue parts dependence, thresholds are related to the nature of the tissue and the vital importance of the part e.g., the difference between head and members in bodies or of leaves, flower petals, stems, branches and trunks in plants. Relative to the relation with exposure, thresholds are different for e.g., between a device fabricator and user or between a plant occasionally exposed to a phone call or permanently to a fixed antenna. The exposure conditions are mainly related to type, NF or FF and the duration of exposure.

The protection of EMF exposures could be managed through design optimization of emitting sources, limiting the use of radiating devices in restricted zones, or establishing zones devoid of EMF radiation as public healthcare centers, public parks, city districts, whole towns, woods, petting zoos, zoological gardens, etc. [16].

This paper aims to evaluate and analyze the looked-for and unwanted consequences of exposure to EMFs in living tissues of humans, fauna and flora. This entails routines strengthening expected purposes as well as those monitoring and defending against undesirable outcomes. The second section is devoted to the analysis of the interactions of EMFs with tissues, involving their thermal BEs of wanted and unsolicited exposures. In the third section, the tasks of blood and plant sap fluids in bio-concerned tissues are analyzed. Section 4 relates to the investigation of the governing EMF, BH equations, and their coupled solution. In Section 5, the tissue's thermal conduct and their EMF exposure adverse effects are discussed. Section 6 explains checking and protecting the exposure's consequences. Section 7 gives conclusions and future recommendations.

2. Interactions of EMFs with Tissues

As mentioned earlier, humans' connections with EMFs may be desired for human well-being and social communication. These fields are primarily in the non-ionizing frequency range and mostly in the radio frequency (RF) and microwave (MW) scales; see Figure 1b. Exposure of these EMFs to living tissues can produce different effects. In the case of a focused confined space as in MW hyperthermia medical interventions or closed cavities, as in MW ovens, exposures in these applications result in the desired thermal BEs [10]. In the case of different telecommunication and transmission tools, the connections and contacts sought result from the connection of RF EMF with humans. Affected devices typically use wireless wave transmission, which exhibits stray fields characterized by field exposure radiation in open space. These unwanted exposures can affect the exposed materials by disrupting their normal functioning [9,17]. In the case of living tissues, RF EMF exposures would create unwanted thermal BEs [10]. As we see, the effects of EMF exposure might be desired in one case but undesirable in the other. Note that the relationship between EMFs and tissues may have particular handlings allowing tissues to interact via radiation. For example, several types of ornamental plants have the ability to absorb EMF radiation, thereby protecting other surrounding living tissues; see e.g., [18]. At this point, highlighting the notion of interaction would be hailed. Two or more entities can interact, that is, one can affect the other. The outcome may be desired, indifferent or undesirable. The number of interaction possibilities will be greater as the entities are more numerous. Considering humans, fauna and flora, these three living entities could be exposed to external phenomena (entities) which can interact with them in an unwanted manner. These phenomena could be divided into two categories of exposure, natural and artificial. The most common natural exposures are lightning, storms, seismic and volcanic activities. Artificial exposures are mainly due to human activities. Such artificial unwanted exposures are considered as pollution to the normal functioning of the three living entities. This is linked to the exposure of living tissues of man, fauna and flora that can produce unwanted thermal BEs. In this case, humans create pollution that interacts with living tissues of humans, fauna and flora, producing harmful effects that reflect the One Health concept [1].

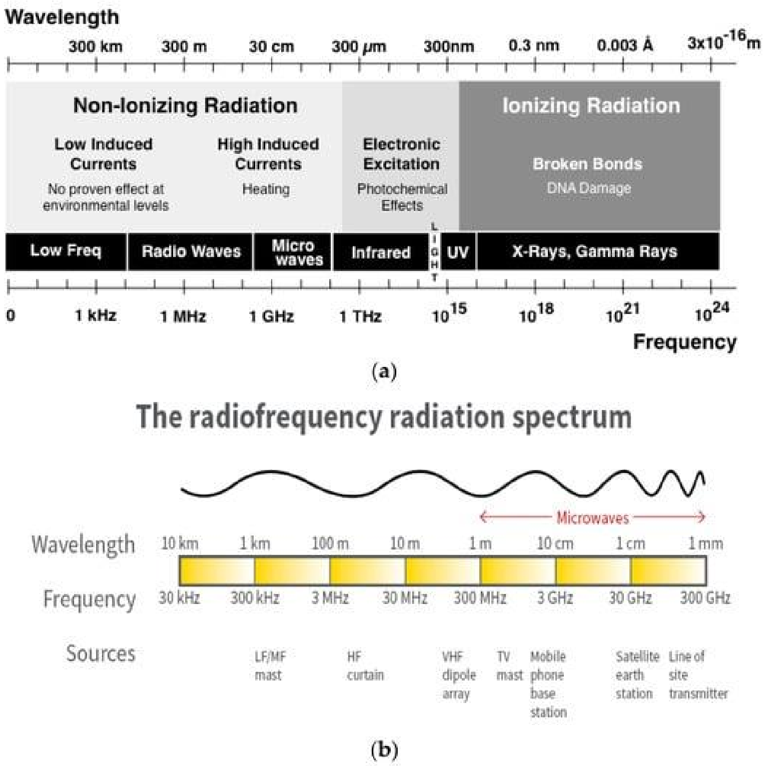

Figure 1. EMF frequency and wavelength ranges. (**a**) Ionizing and non-ionizing; (**b**) RF range.

The practice of mathematical modeling seems essential in the design and analysis of devices and processes involved in thermal BEs. Thus, we can better understand the physical phenomena involved. The thermal BEs affected by desired and undesired EMFs are governed by the EMF equations and the BH equation, as will be discussed in Section 4.

2.1. Desired EMF Thermal BEs

Different applications employ EMF as a production mode of thermal BEs. The most common are related to two categories [10]. The first concerns metal processing, food cooking and drying of different matters such as fruits, wood, paper, etc. using induction (range kHz) for metals heating and MW heating for cooking and drying.

The second relates to medical tissue treatments such as hyperthermia for tumor destruction using different frequencies of heating.

2.1.1. Induction and MW Heating

Induction heating uses wireless induction to induce eddy currents in a conductive material, without direct contact with a heat source [19–23]. A high frequency excitation coil accomplishes this. The resulting flux induces an electromotive force in the conductive metal, which induces electric current to flow. In the case of an induction cooktop, the interior of a metallic vessel surface will be heated in agreement with Faraday's law and the Joule effect, producing a power dissipation loss directing to a temperature rise. This heating mode is mainly used for cooking, conservation and sterilization of food. It could be applied also for different dielectric matter treatments and disinfection of medical instruments. For the cooking action, the involved process behaves, as a thermal-BE, comprising H_2O extraction plus chemical reaction, which transforms raw matter into consumable food.

MW industrial and domestic ovens use a frequency of 2.45 GHz allowing good penetration into food or other materials, so that the heat produced is uniformly distributed in the volume concerned [24–27]. During the heating process, the radiated energy in MW is converted into heat thanks to intermolecular friction forces. The corresponding ovens are used for drying materials by providing energy to water molecules. This thermal energy will be conducted from the interior towards the surface of the material; the water will evaporate through diffusion and dry once the energy exceeds the level needed to completely, remove the moisture. As in induction heating, thermal-BE will transform raw materials into consumables. Note that MW industrial ovens are also used for drying processes of wood, paper and other materials.

Note that humans besides feeding both domestic fauna and flora, use desired EMF thermal BEs to cook these two elements for their food.

2.1.2. Hyperthermia Tissues Medical Therapies

Minimally invasive tissue treatments, which require thin MW antennas, small RF probes or laser fibers introduced directly through the skin or natural pathways for local tissue therapy by thermal damage. Hyperthermia uses the BE of tracked induced heat to adversely disturb tumor evolution. This is done via an artificial increase of temperature of 40–44 °C for 1–1.5 hours. For example, MW hyperthermia aims to raise the temperature of the tumor selectively manner via a dedicated arrangement of antennas with applicators functioning at 434–915 MHz frequency. Thus, such applicators reflect a capacity for tissue penetration creating a regulated concentration of heat in the region of tumor. Again, this thermal-BE permits benefit selective destruction of tumors without damage to healthy adjacent areas [28–33].

2.2. Unwanted EMF BEs

The exposure of EMFs to objects generally produces various effects, which depend on the nature of the exposure source and the exposed elements. Daily used wireless devices working in the non-ionizing frequency range (mainly RF and MW) produce the involved fields. When such exposure occurs accidentally or unintentionally, it can have disruptive effects. This may disrupt the operation of a device, such as an electronic appliance, or a medical instrument, such as an imager. As well, this may affect different living tissues.

2.2.1. Common Thermal BEs

Wide varieties of exposures affect living tissues. Exposure of such tissues to non-ionizing EMF may produce undesirable BEs related to tissue-induced fields, such as electric field E, magnetic induction B or current density J and temperature rise ΔT. Too high values of such induced fields could be dangerous and should be monitored by checking their harmony with the thresholds set by safety standards [34–38]. These BEs are closely linked to the characteristics of the EMF source and the exposed material. The frequency and intensity of the field characterize the source, while the biological and geometric characteristics of the tissues characterize the matter. It may be noted that the needed conditions for desired thermal BEs that are caused indirectly by induction heating or directly by MW heating, are these to be avoided for unwanted exposures.

2.2.2. Uncommon EMF Tissues-Effects

The above-discussed thermal BEs due to EMF exposure are the utmost frequent to the habitual practice of digital communication tools. These BEs do not represent any risk if the tissues-induced fields are in harmony with the thresholds set by safety standards.

Other special personal effects concern fewer people who experience different unusual effects due to such exposure. These will present atypical symptoms, which correspond to two different categories. The first presents several nonspecific signs due to minor exposures with an insignificant interval, well below the limits of safety standards. The second exposes cognitive disorders to long-term exposures. Regarding the first category of people, they are presumed to be hypersensitive to different frequencies of EMF in general. Such electromagnetic hypersensitivity (EHS) includes a characteristic intolerance to EMF atmospheres. The origin of these signs is not proven. Several investigations have been published to understand this inexplicable situation, see for example [39–45]. For the second category of disorders of cognitive functioning, the origin of these is also unfounded and different examinations have been mentioned in the literature, for example [46–48]. At this point, from these investigations, these two categories of atypical symptoms that seem real, their occurrence is connected with EMF although their BE looks non-present. Thus, the exposure brings obliquely through an unknown liaison (for the instant) with the special effects, which are the cause of the signs. Constantly with such a conflict, one can meditate that EMF effects unseen now could arise and clarify these symptoms. It is scientifically problematic to contest the existence of a menace. Such doubt can always rationalize a cautious approach [49]. Due to this challenging circumstance, and awaiting further investigation and better evaluation, individuals with these warning signs could rationally be considered clinically as a chronic sickness, acknowledging that the main origin stays the EMF environment.

Additionally, there are lesser, special tissue effects that are not thermal. This can occur due to excessive tissue-induced EMF values and increased temperature. These can cause molecular disruptions leading to tissue damage [50–61]. Moreover, accidental exposures to EMFs in the ionizing frequency range can result in dangerous adverse health effects associated with molecular disorders involving tissue damage, due to the high energy of photons or particles. However, this class of radiation can be used in medical treatments, for example, X-rays, whose energy level varies from very low for dental X-rays, to particularly high in irradiators intended to sterilize medical utensils. Particular health safety environments condition this type of routine for patients and medical staff.

3. Roles of Blood and Sap Fluids in Tissues

Man, fauna and flora need a circulation of fluids in their tissues allowing their irrigation to continue to live. This includes the blood fluid of humans and wildlife, as well as the sap of flora. The study of BE due to exposure to EMF is closely linked to these fluid circulations. In this section, we will analyze the role of blood and sap circulation in living tissues.

Blood carries oxygen from the lungs and nutrients from the digestive system to all tissues in body parts so they can continue to function and carry carbon dioxide from the tissues back to the lungs. It carries oxygen in the form of an unstable compound—oxyhemoglobin, from the lungs to tissues and fights infections by delivering the hormones throughout the body. Moreover, it carries excretory materials from tissues to the liver, kidneys or skin and other wastes from the digestive system for elimination from the body. The vessels that leave the lungs with oxygen are arteries and those that arrive at the lungs with carbon dioxide are veins. Figure 2 illustrates a schematic representation of the role of blood circulation in body tissues.

The sap fluid circulating in plant tissues plays the role of blood fluid circulating in animal tissues. Two types of sap fluids flow through two corresponding types of plant vessels in opposite directions (from leaves to roots and vice versa). The phloem primarily transports sugars and hormones from leaves to roots through plant tissues and the xylem transports water and minerals in the opposite direction. They act as arteries and veins for blood fluids in animal tissues. Note that sugars and hormones are produced by the exchange of nourished leaves of water and minerals with sunlight, while water and minerals are filtered and absorbed by roots from the soil. Figure 3 schematically shows the role of sap fluids in plant tissues corresponding to blood in the body shown in Figure 2.

It should be noted that in both human fauna and flora, the arterial, venous, phloem and xylem vessels, including their circulating fluids, blood and sap, shown in Figures 2 and 3, are strongly linked to the good functioning of different parts of bodies and plants. In addition, they play an important role in living tissue protection against thermal assaults, particularly thermal BE due to exposure to EMF. Therefore, their representation in the BH equation must be realistic and faithful [16].

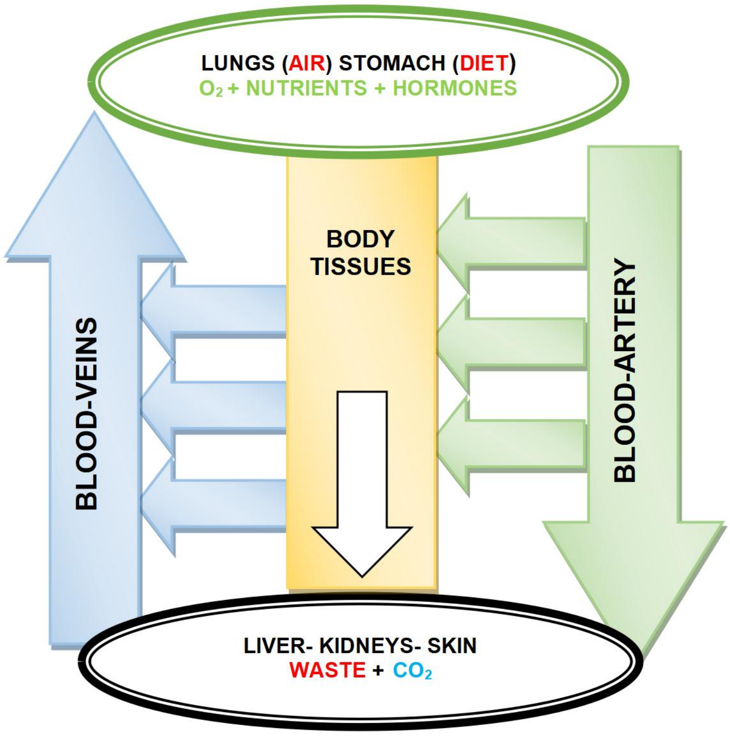

Figure 2. Schematic representation of the role of blood circulation in body tissues.

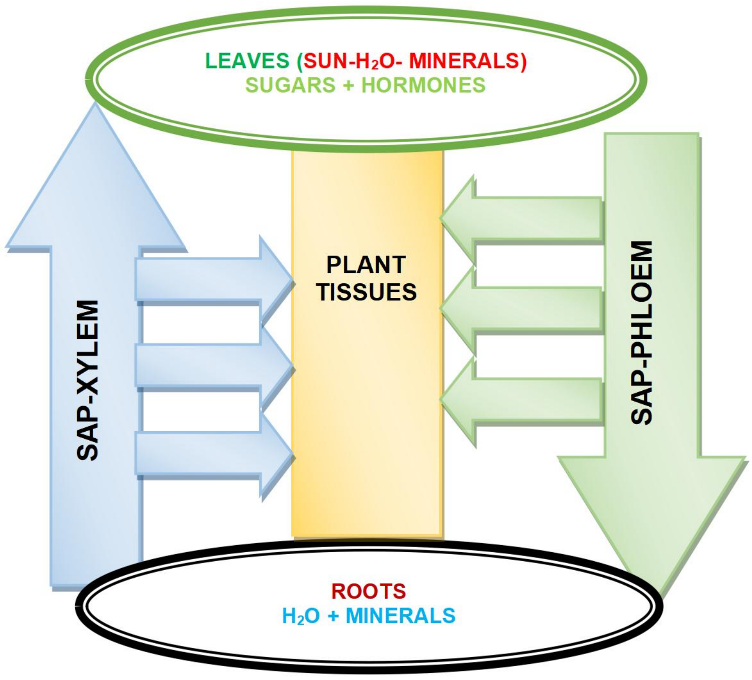

Figure 3. Schematic illustration of the role of sap fluids in plant tissues.

4. Governing Equations

This section is dedicated to the mathematical investigation of the EMFs' exposure thermal effects. The electromagnetic (EM) and heat transfer (HT) phenomena run EMF exposure thermal effect. In the case of living tissues, the HT will occur in a BH representation. The tissue temperature rise will be determined by the BH phenomenon initiated by a heat source corresponding to the EM power dissipated in the material concerned, which can be determined by the EM phenomenon. The EMF and BH equations govern thermal desired and unwanted BEs due to EMF exposure.

4.1. EMF Equations

The general EMF four equations, in their differential form, based on Maxwell's microscopic local equations [62] are given by $\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$ (Maxwell—Faraday), $\nabla \times \mathbf{H} = \sigma \mathbf{E} + \partial_t \mathbf{D}$ (Maxwell—Ampère), $\nabla \cdot \mathbf{D} = \rho_e$ (Maxwell—Gauss), and $\nabla \cdot \mathbf{B} = 0$ (Maxwell—Thomson).

For harmonic fields, the EMF Equations (1)–(4) can be given by:

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

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

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

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{4}$$

In the above EMF equations, **H** and **E** are the vectors of the magnetic and electric fields in A/m and V/m, **B** and **D** are the vectors of the magnetic and electric inductions in T and C/m^2, **A** and V are the magnetic vector and electric scalar potentials in W/m and volt. **J** and $\mathbf{J_e}$ are the vectors of the total and source current densities in A/m^2, σ is the electric conductivity in S/m, ρ_e is the volume density of electric charges in C/m^3, and ω is the angular frequency = 2πf, f is the frequency in Hz of the exciting EMF. The symbol ∇ is a vector of partial derivative operators, and its three possible implications are gradient (product with a scalar field), divergence and curl (dot and cross products respectively, with a vector field). The symbol ∂_t is the operator of the partial time derivative. The magnetic and electric comportment laws respectively between **B/H** and **D/E** are represented by the permeability μ and the permittivity ε in H/m and F/m.

The source term in the EMF Equations (1)–(4) is the excitation current density $\mathbf{J_e} = \sigma\, \mathbf{E_e} = j\, \omega\, \mathbf{De} = j\, \omega\, \varepsilon\, \mathbf{E_e}$. The choice of the form of the source term depends on the nature of the exposure, NF, FF, etc. and the exposed material nature.

The volume density of the dissipated power P_d in dielectric materials (biological tissues) and the corresponding specific absorption rate (SAR) are given by Equations (5) and (6):

$$P_d = \omega \cdot \varepsilon'' \cdot E^2/2 \tag{5}$$

$$SAR = P_d/\rho = \omega \cdot \varepsilon'' \cdot E^2/(2\rho) \tag{6}$$

In Equations (5) and (6), the parameter: ε" is the imaginary part of the complex permittivity of the absorbing material and ρ is the material density in kg/m^3. E is the absolute peak value of the electric field strength in V/m and SAR is in W/kg. The power dissipation in W/m^3 given by Equation (5) relates to the foremost dielectric heating of EMF energy loss. Notice that the imaginary part ε" of the (frequency-dependent) permittivity ε is a measure of the ability of a dielectric material to convert EMF energy into heat, also termed dielectric loss. The real part ε' of the permittivity is the effect of capacitance resulting in non-dissipative reactive power.

The volume density of power dissipations given by Equation (5) will be used in the coupling of EMF and BH equations.

4.2. BH Equation

Concerning the HT problem, generally the heat flux corresponding to the rate of thermal energy flowing across a surface in a given medium is produced by a temperature difference gradient. Such a gradient can generate heat fluxes in solids (by conduction), in gases or liquids (by convection) and via space waves (by radiation). Heat is often, transferred in a combination of these three modes and occurs irregularly. For example, heat flows through the ground (conduction) and the body envelope (mainly convection and radiation) affects the thermal environment of a standing body. Generally, the quantity of heat absorbed by an element of tissue or more largely of a lossy dielectric can be given as Equation (7):

$$\Delta Q = c\, m_s\, \Delta T \tag{7}$$

In Equation (7), Q is the heat energy dissipated in joule (J), m_s is the mass of the substance in kg, ΔT is the change in substance temperature in °C, c is the specific heat of the substance in J/(kg °C). The corresponding power will be $\Delta P = \Delta Q/\Delta t$. The volume specific power will be Equation (8):

$$\Delta P_v = \Delta P/v = c\,(m_s/v)\,(\Delta T/\Delta t) = c\,\rho\,(\Delta T/\Delta t) \tag{8}$$

In Equation (8), P is the power in watt (W), t is the time in (s), P_v is the power per unit volume in W/m^3, v is the volume in m^3, and ρ is the density in kg/m^3.

The HT equation providing the volume specific power of (8) in its differential form is given by Equation (9):

$$c\,\rho\,\partial T/\partial t = \nabla\cdot(k\,\nabla T) \tag{9}$$

In Equation (9) k is thermal conductivity in W/(m· °C).

Considering the case of living tissues, we have to consider in Equation (9) a self tissue heat source P_t and the involved convective heat transfer via irrigating fluid corresponding to the considered part of tissue. The convective heat transfer coefficient in the fluid h_f in W/ (m^2 °C) can be defined through the heat flux in (W/m^2) = $h_f \cdot \Delta T$ or through the power ΔP in (W) = $h_f\, S\, \Delta T$, from Equation (8) and are given by Equations (10) and (11):

$$\Delta P_v = h_f\,(S/v)\,\Delta T = (h_f/\chi)\,\Delta T = c_f\,\rho_f\,(\Delta T/\Delta t) \tag{10}$$

Then

$$h_f = c_f\,\rho_f\,p_f\,\chi \tag{11}$$

In Equations (10) and (11), S is the surface of the tissue part concerned in m^2, χ is the thickness of the tissue part in m. Also c_f, ρ_f, are respectively fluid, specific heat in J/(kg °C), density in kg/m^3 and perfusion rate in 1/s.

On the other hand, we have to consider in Equation (9) the external heat source related to the EMF exposure, P_d or SAR given by Equations (5) and (6).

Under these conditions, Equation (9) will be extended to a tissue BH equation, which can be presented as Equation (12):

$$c\,\rho\,\partial T/\partial t = \nabla\cdot(k\,\nabla T) + P_d + P_t + c_f\,\rho_f\,p_f\,(T_f - T) \tag{12}$$

In Equation (12), P_t is the tissue self-heat source in W/m^3, T_f and T are respectively the fluid temperature and the local temperature of tissue in °C. Equation (12) corresponds to bio-heat tissues accounting for EMF exposure. This equation has a form similar to Penne's bio-heat equation [9,10,17,63] related to human tissues and convective heat transfer in blood. As mentioned earlier, plant sap plays the role of blood in animals. In addition, Phloems and Xylems for sap play the role of arteries and veins for blood. Note that in Penne's bio-heat equation, the term P_t in Equation (12) is related to tissues' metabolic heat and corresponds to plant tissues' internal heat. Also, the last term in Equation (12) representing convection fluid heat transfer corresponds to animal blood or plant sap. The orders of magnitude of the relative values of the parameters related to animal and plant tissues as well as blood and sap are different due to the different nature of animal and plant tissues. The different values of parameters involved in Equation (12) relative to P_t, c_f, ρ_f, and p_f depend on the tissue type and the specific part of this tissue. Note that the contribution of P_d is much more important relative to P_t (see Section 5).

4.3. Coupled Solution of EMF and BH Equations

Equations (1)–(4) and (12) can be solved in a coupled way. Given the geometric complexity and inhomogeneity of tissue, the solution must be local in the tissue using discretized 3D techniques as finite elements [64–72] in the appropriate element of the tissue. The discretized 3D elements are volume parts enclosed in surface elements, each encircled by edge elements, each end by two nodes. For example, a tetrahedral element involves four triangular faces, six straight edges, and four nodes. The fields could be defined at nodes, edges, faces or volume depending on the nature of the field as requirements of continuity, etc. The coupling of the EMF and BH equations is weak due to the distant values of their time constants [9,10,17]. Thus, an iterative solution provides in the tissue the local distributions of the induced values of the fields $\mathbf{E_i}$, $\mathbf{B_i}$, and $\mathbf{J_i}$, and hence P_{di}, SAR_i, and ΔT_i. The parameters concerned are those of the tissue properties, ε, P_t, c_f, ρ_f, p_f, etc. The geometry involved is related to the shape of the portion of tissue concerned. Exposure conditions are taken into account via the nature of the EMF source (strength and frequency) and the exposure interval. Note that consideration of the exposure source is different for near or far field cases. For NF radiation, the source is generally involved in the solution domain as a focused field. In the case of FF, which is generally of homogeneous value, the source is imposed uniformly over the entire exposed surface of the object. The different parameters in equations (1–4 and 12) could be found in literature or measured [73–76].

5. Tissues Heating Adverse Effects

In this section, we will analyze the thermal behavior of BE and summarize the possible adverse consequences on tissues due to such an effect. As mentioned previously, heating by high frequency EMFs focuses directly inside tissues, as in MW heating [10]. Additionally, high frequencies such as in the RF and MW range exhibit the energetic ability to rapidly heat tissues [9]. Added to this, is the weakness of the tissues to resist the uneven increase in temperature, which can occur mainly in those parts of the tissues where the flow of fluid (blood or sap) is deficient, which establishes the main ways of dealing with excessive heat. These three characteristics, internal concentration, rapid heating and low fluid flow, are not integrated into the natural self-protection of the tissue, which depends on heat transfer by conduction and convection to sunlight and the hot environment. Therefore, the main detrimental consequence on tissues exposed to high frequency EMF would be rapid heating inside the defenseless parts of the tissues, without a proper self-preservation perspective to defend the key functions of the tissues [9,13]. Note that in addition to possibly damaging parts of tissue, excessive and permanent fields can trigger non-thermal effects, that can stimulate nerves, muscles and excitable structures.

The SAR is given by Equation (6) and the exposure interval Δt characterize the behavior of EMF exposures. SAR is directly related to frequency, field strength and tissue parameters. See Section 7 for more details on how different parameters affect temperature rise. Common SAR values for adverse effects of tissue exposure are 4 to 10 W/kg. The affected frequency range involving RF and MW thermal BE is 105–0.3 · 1012 Hz, which produces non-ionizing radiation. The Function of the nature of the tissues, long exposure intervals could cause temperature rises exceeding thresholds (see next section) fixed by standards and resulting in adverse BE.

6. Monitoring and Defense of EMF Effects

The obtained local 3D distributions regarding the induced EMFs and ΔT make it possible to accomplish two main actions, which are the control of the unwanted effects as well as the protection strategies concerning unwanted radiated fields. An illustrative example of distributions of induced B and E fields in a human body due to exposure to a wireless energy transfer device in an electric vehicle [9] is given in Figure 4.

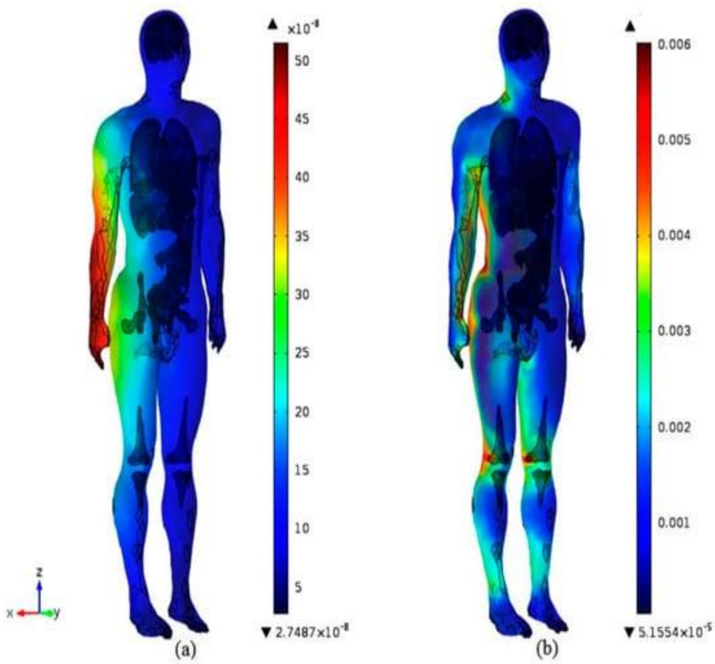

Figure 4. Distribution of induced fields in a human body. (**a**) Magnitude of B (T); (**b**) Magnitude of E (V/m) [9].

6.1. Control Methodology of Unwanted Radiation

In the case of human and animal tissues, the different unwanted predicted field distributions are checked by comparison to thresholds [9,10,17,34–36]. These thresholds are fixed in the function of nature of the exposed tissue (body part, adult, child, animal, etc.), the relation of the source to the exposed subject (fabrication, installation, user, etc.), and the exposure condition (distance, concentration, duration, etc.). In the case of plant tissues, these thresholds correspond to the safety limits of public exposure, e.g., [37,38]. Such thresholds could be set for different, kinds of plants, parts of a plant, atmospheric circumstances of the plant location and corroborated exposure duration and conditions. Figure 5 summarizes the EMF-BH models, a weakly coupled solution strategy accounting for the nature of the exposure source and the tissue parameters. The induced fields, in the case of unwanted exposure, are controlled vs. thresholds in the whole tissue.

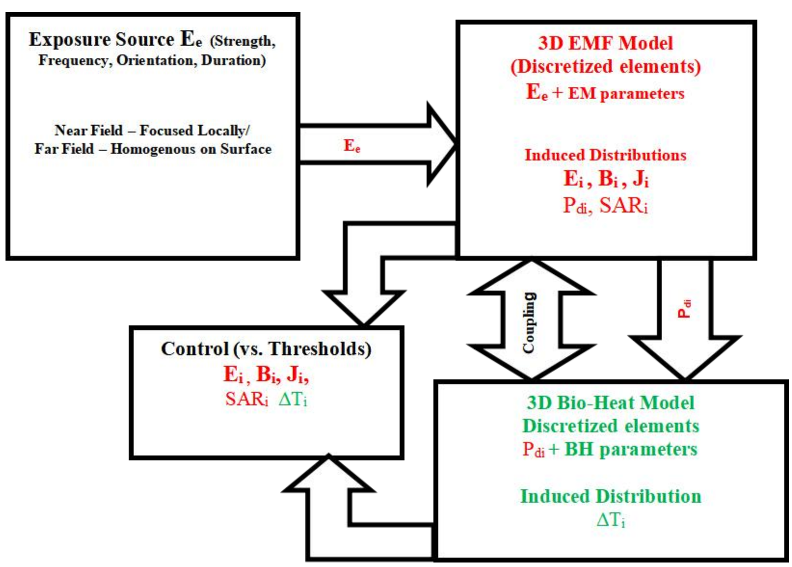

Figure 5. Schematic illustration of the EMF-BH models weak coupled solution strategy accounting for the exposure conditions and the control of different unwanted predicted field distributions.

6.2. Protection Strategies Against Unwanted Exposures

As mentioned previously, the most significant disruptions to terrestrial biodiversity are caused by human-to-nature relationships. This involves, in addition to man, fauna and flora: birds, animals, insects and plants. Protection of these species from RF-EMF could be achieved by two main protection strategies: source shielding and restricting exposure zones. The first is directly linked to radiation sources by reducing their stray fields via shielding technologies [77–82]. This concerns the entire environment, including humans, animals, electronic devices, etc. This protection strategy is not obvious because it is limited by the operating principle of RF wireless devices based on the radiation of electromagnetic waves. The only way to implement such protection is to limit their emission capacity and therefore their performance in restricted protected areas. Thus, the mention of this strategy brings us to the second protection option. This involves the management of restricted areas devoid of radiating devices. This can concern public parks, urban neighborhoods or entire cities [83–85]. This protection option focuses largely on anthropogenic innovations and their links with biodiversity and nature, thus deliberating on the One Health concept [1].

7. Discussion

In this manuscript, the investigation of BEs due to the interaction of EMFs with living tissues of humans, fauna and flora, has illustrated that such a topic is thoroughly beneficial. At this stage, various questions deserve to be commented on:

Behavior of tissues temperature rise: In the tissue bio-heat Equations (1) and (2), the terms P_t and P_d, denoting tissue self-heat and external-heat volume power densities sources. Multiplied by the concerned tissue volume and the exposure time interval, these will give the total heat internal-external energy source $\Delta Q = (P_t + P_d) \cdot v_t \cdot \Delta t$ in J. Considering the case of humans, mammals, other animals and fauna in general this energy corresponds to tissue, metabolic and absorbed EMF exposure parts. The first is characterized generally by the basal metabolic rate (BMR) in J/s and the second by the SAR in W/kg. BMR is the energy needed by a body to perform elementary functions such as breathing, temperature regulation, blood circulation, cellular development, hair growth, and hormone fabrication. These functions correspond to what the body does at rest. BMR is a part of metabolism (converting food + O_2 into energy). BMR is almost 75% of burned energy at rest, which is almost 50 calories per hour (0.05815 J/s) for the average human. Burned energy relative to day activity of humans is between 100 and 800 calories (1 cl = 4.1868 J) including 10% to digest food. Noting that the average values of tissue parameters are ($c = 3.\ 10^3$, $\rho = 10^3$, $k = 0.5$), and approximately ($\Delta Q = c\ ms\ \Delta T$). The temperature rise due to EMF exposure will be $\Delta T_d = SAR \cdot \Delta t / c$ and the temperature rise due to internal metabolism $\Delta T_t = BMR \cdot \Delta t / (c\ M)$, with M as the body mass. This indicates that the contribution to temperature rise is much higher due to EMF exposure than internal metabolism. The case of plants relative to the internal tissue self-heat reflects the same observation. The total general tissue temperature rise will be approximately as Equation (13):

$$\Delta T = \omega \cdot \varepsilon'' \cdot \Delta t \cdot E^2 / (2\rho c) \tag{13}$$

Equation (13) illustrates that the temperature rises ΔT increase as the frequency f, the imaginary part of the tissue complex permittivity ε'', the exposure duration Δt, the electric field as $E^2/2$ and inversely as the product of the tissue density ρ and the tissue specific heat c.

Reduction of EMF radiations for small sources: In Section 6.2, strategies for protecting against unwanted exposures through radiation reduction were explored. A lesser universal strategy to reduce EMF radiation for small sources could be the use of EMF absorbers [86,87]. Moreover, an example of such a strategy involves reducing radiation emitted by portable electronic devices or Wi-Fi sources, by using several types of ornamental plants. In addition to beautifying the scenery, these plants can absorb part of the radiation, thus reducing possible harmful effects. Such an act may be helpful in the case of persons with EHS mentioned in Section 2.2.2. One of the most effective plants in this area is the snake plant (Dracaena Trifasciata), when placed near the radiation source; it reflects a radiation absorption capacity reducing its value by almost 30% [18,88].

Complexity and living tissue behavior: In general, the computations of 3D distributions of the induced EMFs in body tissues, as illustrated in Figure 4, need a sufficiently accurate body model. Figure 6 shows a structural body model and its various organs and tissues. Such a high-resolution tissue model is in harmony with the numerical methodologies used for the calculation of induced fields in human tissues. In theory, when living tissues are exposed to EMFs, the effects occur in real time. The mathematical modeling carried out to evaluate these effects is supposed to account for the real-time behavior of tissues. This problem faces various difficulties, the main ones being computational complexities, and tedious tasks linked to calculation time. The main cause of these difficulties is the nonlinearity of biological tissues reflecting complex constitutive laws representing the deformation and displacement behaviors of elastic tissues. Complexity often occurs in a set of compound processes [89] and could be encountered in various areas, e.g., neuroscience [90], Earth climate [91], evolutionary biology [92], space vehicles [93], economics of fair division [94], game theory of strategic interactions [95], political science [96] and history [97]. These compound processes interact in complex actions according to nonlinear interdependent spatiotemporal behaviors. Such processes could form a non-complex action when they interact simply. Returning to the complex behavior of living tissues, more realistic approximate constitutive laws, adapted computational techniques or combined methodology could solve this open research problem.

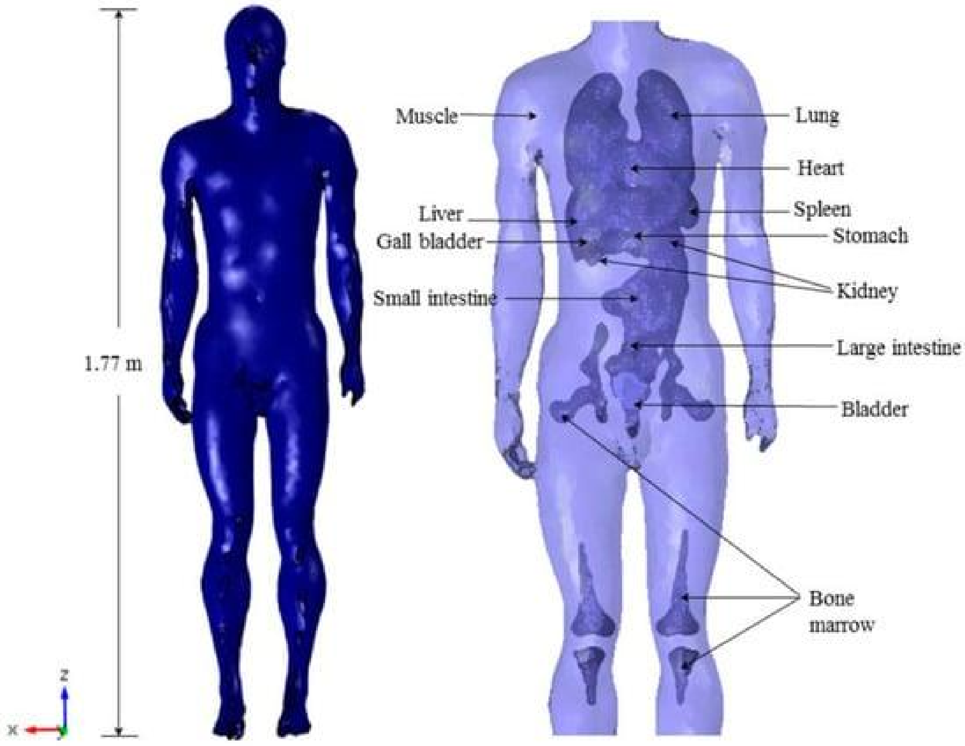

Figure 6. High-resolution anatomical whole body model and its different organs and tissues [9].

8. Conclusions

In this manuscript, the analysis and evaluation carried out on the biological effects due to the interaction of electromagnetic fields with living tissues have shown that such a subject is quite a valuable fact. The contribution focused on the evaluation and analysis of the desired and unsolicited effects of such a relation with living tissues in general. Routines supporting expected functions as well as those controlling and protecting against unwanted effects have been proposed. The governing electromagnetic, bio-heat equations, and their coupled solution were analyzed. Monitoring and defending the adverse effects of exposures were discussed. An obvious fact relating to this last point is that the only way to protect different tissues against sources of EMF radiation is to limit their emission capacity and therefore their performance in restricted protected areas, otherwise to manage regulated areas devoid of radiant devices. We thus find the One Health concept, the protection of humans, animals and biodiversity against disturbances generated by human activity is a unified preservation corresponding to a crucial issue.

The following various recommendations for further investigation may be encouraged: Explore the different categories of living tissues in their environments likely to be radiated by near or far fields. Establish experimentally the bio-thermal-electromagnetic parameters necessary for models of different parts of tissues accounting for their environments. Setting thresholds for electromagnetic and thermal fields for the main vulnerable parts of living tissues. Explore the complex behavior of living tissues through constitutive laws, adapted computational techniques, or a combined methodology.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. One Health. Available online: https://www.who.int/europe/initiatives/one-health (accessed on 14 March 2024).
2. Petroulakis, N.; Mattsson, M.O.; Chatziadam, P.; Simko, M.; Gavrielides, A.; Yiorkas, A.M.; Zeni, O.; Scarfi, M.R.; Soudah, E.; Otin, R. et al. NextGEM: Next-Generation Integrated Sensing and Analytical System for Monitoring and Assessing Radiofrequency Electromagnetic Field Exposure and Health. *Int. J. Environ. Res. Public Health* **2023**, *20*, 6085. [CrossRef]
3. Cirimele V.; Freschi F.; Giaccone L.; Pichon L.; Repetto M. Human Exposure Assessment in Dynamic Inductive Power Transfer for Automotive Applications. *IEEE Trans. Magn.* **2017**, *53*, 1–4. [CrossRef]
4. Lagorio, S.; Blettner, M.; Baaken, D.; Feychting, M.; Karipidis, K.; Loney T.; Orsini, N.; Röösli, M.; Paulo, M.S.; Elwood, M. The Effect of Exposure to Radiofrequency Fields on Cancer Risk in the General and Working Population: A Protocol for a Systematic Review of Human Observational Studies. *Environ. Int.* **2021**, *157*, 106828. [CrossRef]
5. Pophof, B.; Burns, J.; Danker-Hopfe, H.; Dorn, H.; Egblomassé-Roidl, C.; Eggert, T.; Fuks, K.; Henschenmacher, B.; Kuhne, J.; Sauter, C. et al. The Effect of Exposure to Radiofrequency Electromagnetic Fields on Cognitive Performance in Human Experimental Studies: A Protocol for a Systematic Review. *Environ. Int.* **2021**, *157*, 106783. [CrossRef]
6. 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. [CrossRef]
7. Chikha, W.B.; Zhang, Y.; Liu, J.; Wang, S.; Sandeep, S.; Guxens, M.; Veludo, A.F.; Röösli, M.; Joseph, W.; Wiart, J. Assessment of Radio Frequency Electromagnetic Field Exposure Induced by Base Stations in Several Micro-Environments in France. *IEEE Access* **2024**, *12*, 21610–21620. [CrossRef]
8. Sivani, S.; Sudarsanam, D. Impacts of Radio-Frequency Electromagnetic Field (Rf-Emf) from Cell Phone Towers and Wireless Devices on Biosystem and Ecosystem—A Review. *Biol. Med.* **2012**, *4*, 202–216. [CrossRef]
9. Razek, A. Biological and Medical Disturbances Due to Exposure to Fields Emitted by Electromagnetic Energy Devices—A Review. *Energies* **2022**, *15*, 4455. [CrossRef]
10. 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. [CrossRef]
11. Ozel, H.B.; Cetin, M.; Sevik, H.; Varol, T.; Isik, B.; Yaman, B. The Effects of Base Station as an Electromagnetic Radiation Source on Flower and Cone Yield and Germination Percentage in Pinus Brutia Ten. *Biol. Futur.* **2021**, *72*, 359–65. [CrossRef]
12. Khan, M.D.; Ali, S.; Azizullah, A.; Shuijin, Z. Use of Various Biomarkers to Explore the Effects of Gsm and Gsm-Like Radiations on Flowering Plants. *Environ. Sci. Pollut. Res.* **2018**, *25*, 24611–14628. [CrossRef]
13. Tran, N.T.; Jokic, L.; Keller, J.; Geier, J.U.; Kaldenhoff, R. Impacts of Radio-Frequency Electromagnetic Field (Rf-Emf) on Lettuce (Lactuca Sativa)-Evidence for Rf-Emf Interference with Plant Stress Responses. *Plants* **2023**, *12*, 1082. [CrossRef]

14. Pawełek, A.; Owusu, S.A.; Cecchetti, D.; Zielińska, A.; Wyszkowska, J. What Evidence Exists of Crop Plants Response to Exposure to Static Magnetic and Electromagnetic Fields? A Systematic Map Protocol. *Environ. Evidence* **2022**, *11,* 37. [CrossRef]
15. Ayesha, S.; Abideen, Z.; Haider, G.; Zulfiqar, F.; El-Keblawy, A. et al. Enhancing Sustainable Plant Production and Food Security: Understanding the Mechanisms and Impacts of Electromagnetic Fields. *Plant Stress* **2023**, *9*, 100198. [CrossRef]
16. Razek, A. Analysis and Control of Ornamental Plants Responses to Exposure to Electromagnetic Fields. *Ornamental Plant Res.* **2024**, *4*, e009. [CrossRef]
17. Razek, A. Assessment of EMF Troubles of Biological and Instrumental Medical Questions and Analysis of Their Compliance with Standards. *Standards* **2023**, *3*, 227–239. [CrossRef]
18. Lestari, M.; Sulhadi, S.; Sutikno, S. The Effect of Ornamental Plants on Reducing the Intensity of Electromagnetic Wave Radiation. *Phys. Comm.* **2023**, *7*, 35–42. [CrossRef]
19. Mühlbauer, A. History Of Induction Heating and Melting. Vulkan-Verlag GmbH Publications: Essen, Germany, 2008.
20. Watanabe, T.; Nagaya, S.; Hirano, N.; Fukui, S. Elemental Development of Metal Melting by Electromagnetic Induction Heating Using Superconductor Coils. *IEEE Trans. Appl. Supercond*. **2016**, *26*, 1–4. [CrossRef]
21. Biswal, SK; Pal, S. Numerical Investigation of the Dimension Factor of Hairpin Coil for Sustainable Induction Heating. In *Recent Advances In Manufacturing Modelling And Optimization: Select Proceedings of RAM 2021*; Springer Nature Singapore: Singapore, 2022, pp. 11–19. [CrossRef]
22. Zhu, G.; Liu, X.; Li, L.; Zhu, J. A Novel Nonlinearity Marginalization Technique for Effective Solution of Induction Heating Problems by Cell Method. *J. Phys. D: Appl. Phys*. **2020**, *53*, 245502. [CrossRef]
23. Vishnuram, P.; Ramachandiran, G.; Sudhakar Babu, T.; Nastasi, B. Induction Heating in Domestic Cooking and Industrial Melting Applications: A Systematic Review on Modelling, Converter Topologies and Control Schemes. *Energies* **2021**, *14*, 6634. [CrossRef]
24. Hu, Q.; He, Y.; Wang, F.; Wu, J.; Ci, Z.; Chen, L.; Xu, R.; Yang, M.; Lin, J.; Han, L. et al. Microwave Technology: A Novel Approach to the Transformation of Natural Metabolites. *Chinese Medicine* **2021**, *16*, 87. [CrossRef]
25. Kumar, C.; Karim, M.A. Microwave-Convective Drying of Food Materials: A Critical Review. *Crit. Rev. Food Sci. Nutr.* **2019**, *59*, 379–394. [CrossRef]
26. Sekkak, A.; Pichon, L.; Razek, A. 3-D Fem Magneto-Thermal Analysis in Microwave Ovens. *IEEE Trans. Magn.* **1994**, *30*, 3347–3350. [CrossRef]
27. Ge, C.; Duan, B.; Lou, S.; Qian, S.; Wang, W. On Improving Convergence Characterization to Solve the Electromagnetic—Thermal Model. *IEEE Trans. Microwave Theory Tech.* **2021**, *69,* 3624–3634. [CrossRef]
28. Rodrigues, D.B.; Ellsworth, J.; Turner, P. Feasibility of Heating Brain Tumors Using a 915 MHz Annular Phased-Array. IEEE Antennas Wirel. *Propag. Lett.* **2021**, *20*, 423–427. [CrossRef]
29. Zastrow, E.; Hagness, S.C.; Van Veen, B.D.; Medow, J.E. Time-Multiplexed Beamforming for Noninvasive Microwave Hyperthermia Treatment. *IEEE Trans. Biomed. Eng.* **2011**, *58*, 1574–1584. [CrossRef]
30. Redr, J.; Pokorny, T.; Drizdal, T.; Fiser, O.; Brunat, M.; Vrba, J.; Vrba, D. Microwave Hyperthermia of Brain Tumors: A 2D Assessment Parametric Numerical Study. *Sensors* **2022**, *22*, 6115. [CrossRef]
31. Rittersdorf, I.M.; Hoff, B.W.; Richardson, A.S.; Martin, S.A.; Yakovlev, V.; Kim, P.; Schumer, J. A 1-D Model for the Millimeter-Wave Absorption and Heating of Dielectric Materials in Power Beaming Applications. *IEEE Trans. Plasma Sci.* **2021**, *49*, 695–702. [CrossRef]
32. Sekkak, A.; Kanellopoulos, V.N.; Pichon, L.; Razek, A. A Thermal and Electromagnetic Analysis in Biological Objects Using 3d Finite Elements and Absorbing Boundary Conditions. *IEEE Trans. Magn*. **1995**, *31*, 1865–1868. [CrossRef]
33. Bellizzi, G.G.; Drizdal, T.; van Rhoon, G.C.; Crocco, L.; Isernia, T.; Paulides, M.M. The Potential of Constrained SAR Focusing for Hyperthermia Treatment Planning: Analysis for the Head & Neck region. *Phys. Med. Biol.* **2019**, *64*, 015013. [CrossRef]
34. International Commission on Non-Ionizing Radiation Protection. Guide-Lines for Limiting Exposure to Time-Varying Electric and Magnetic Fields for Low Frequencies (1 Hz–100 kHz). *Health Phys*. **2010**, *99*, 818–836. [CrossRef]
35. 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. [CrossRef]
36. IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz," in IEEE Std C95.1-2019 (Revision of IEEE Std C95.1-2005/ Incorporates IEEE Std C95.1-2019/Cor 1-2019) , vol., no., pp.1 – 312, 4 Oct. 2019. Available online: https://ieeexplore.ieee.org/document/8859679 (accessed on 10 January 2024).
37. Scientific Evidence for Cell Phone Safety. Available online: https://www.fda.gov/radiation-emitting-products/cell-phones/scientific-evidence-cell-phone-safety (accessed on 4 January 2024).
38. 1999/519/EC: Council Recommendation of 12 July 1999 on the Limitation of Exposure of the General Public to Electromagnetic Fields (0 Hz to 300 GHz). Available online: https://eur-lex.europa.eu/eli/reco/1999/519/oj (accessed on 4 January 2024).
39. Feychting, M.; Ahlbom, A.; Kheifets, L. EMF and Health. *Annu. Rev. Public Health* **2005**, *26*, 165–189. [CrossRef]

40. 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. [CrossRef]
41. Advocacy for a Cognitive Approach to Electro Hypersensitivity Syndrome. Available online: https://www.researchgate.net/publication/339794948 (accessed on 4 January 2024).
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. [CrossRef]
43. Rubin, G.J.; Nieto-Hernandez, R.; Wessely, S. Idiopathic Environmental Intolerance Attributed to Electromagnetic Fields (Formerly 'Electromagnetic Hypersensitivity'): An Updated Systematic Review of Provocation Studies. *Bio. Electromagn*. **2010**, *31*, 1–11. [CrossRef]
44. Huang, P.C.; Chiang, J.C.; Cheng, Y.Y.; Cheng, T.-J.; Huang, C.-Y.; Chuang, Y.-T.; Hsu, T.; Guo, H.-R. Physiological Changes and Symptoms Associated with Short-Term Exposure to Electromagnetic Fields: a Randomized Crossover Provocation Study. *Environ. Health* **2022**, *21*, 31. [CrossRef]
45. Genuis, S.J.; Lipp, C.T. Electromagnetic Hypersensitivity: Fact or fiction? *Sci. Total Environ.* **2012**, *414*, 103–112. [CrossRef]
46. 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. [CrossRef]
47. Curcio, G. Exposure to Mobile Phone-Emitted Electromagnetic Fields and Human Attention: No Evidence of a Causal Relationship. *Front. Public Health* **2018**, *6*, 42. [CrossRef]
48. Valentini, E.; Ferrara, M.; Presaghi, F.; De Gennaro, L.; Curcio, G. Systematic Review and Meta-Analysis of Psychomotor Effects of Mobile Phone Electromagnetic Fields. *Occup. Environ. Med.* **2010**, *67*, 708–716. [CrossRef]
49. Sunstein, C.R. Beyond the Precautionary Principle. *Univ. Pa Law Rev.* **2003**, *151*, 1003–1058. [CrossRef]
50. Ramos, V.; Suarez, O.J.; Febles-Santana, V.M.; Suarez-Rodriguez, D.S.; Aguirre, E.; De-Miguel-Bilbao, S.; Marina, P.; Rabassa-Lopez-Calleja, L.E.; Celaya-Echarri, M.; Falcone, F. 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. [CrossRef]
51. 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. [CrossRef]
52. Scientific Committee on Emerging and Newly Identified Health Risks. Opinion on Potential Health Effects of Exposure to Electromagnetic Fields (EMF); European Commission: Luxembourg, 2015. Available online: https://health.ec.europa.eu/document/download/059a98d2-07fa-4575-b4a0-ba9f6c4391e0_en?filename=scenihr_o_041.pdf (accessed on 10 January 2024).
53. Sánchez-Hernández, D.A. *High Frequency Electromagnetic Dosimetry*; Artech House, Inc.: Norwood, MA, USA, 2009.
54. Wust, P.; Kortüm, B.; Strauss, U.; Nadobny, J.; Zschaeck, S.; Beck, M.; Stein, U.; Ghadjar, P. Non-Thermal Effects of Radiofrequency Electromagnetic Fields. *Sci. Rep.* **2020**, *10*, 13488. [CrossRef]
55. Zradzi ´nski, 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. [CrossRef]
56. 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. [CrossRef]
57. Leach, V.; Weller, S.; Redmayne, M. A Novel Database of Bio-Effects from Non-Ionizing Radiation. *Rev. Environ.* Health **2018**, *33*, 273–280. [CrossRef]
58. Dürrenberger, G.; Fröhlich, J.; Röösli, M.; Mattsson, M.O. EMF Monitoring—Concepts, Activities, Gaps and Options. *Int. J. Environ. Res. Public Health* **2014**, *11*, 9460–9479. [CrossRef]
59. Röösli, M.; Frei, P.; Bolte, J.; Neubauer, G.; Cardis, E.; Feychting, M.; Gajsek, P.; Heinrich, S.; Joseph, W.; Mann, S. et al. Conduct of a Personal Radiofrequency Electromagnetic Field Measurement Study: Proposed Study Protocol. *Environ. Health* **2010**, *9*, 9–23. [CrossRef]
60. 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 18 February 2024).
61. Cancer Research for Cancer Prevention. Available online: https://www.aws.iarc.who.int/featured-news/new-world-cancer-report/ (accessed on 11 January 2023).
62. Maxwell, JC. VIII. A Dynamical Theory of the Electromagnetic Field. *Philos. Trans. Royal Soc.* **1865**, *155*, 459–512.
63. Pennes, H.H. Analysis of Tissue and Arterial Blood Temperatures in the Resting Human Forearm. *J. Appl. Physiol.* **1998**, *85*, 5–34. [CrossRef]
64. Nunes, A.S.; Dular, P.; Chadebec, O.; Kuo-Peng, P. Subproblems Applied to a 3-D Magnetostatic Facet FEM Formulation. *IEEE Trans. Magn.* **2018**, *54*, 1–9. [CrossRef]
65. Li, G.; Ojeda, J.; Hoang, E.; Gabsi, M.; Lecrivain, M. Thermal–Electromagnetic Analysis for Driving Cycles of Embedded Flux-Switching Permanent-Magnet Motors. *IEEE Trans. Veh. Technol.* **2012**, *61,* 140–151. [CrossRef]

66. Piriou, F.; Razek, A. Numerical Simulation of a Nonconventional Alternator Connected to a Rectifier. *IEEE Trans. Energy Convers*. **1990**, *5*, 512–518. [CrossRef]
67. Caractérisation électrique des tissus biologiques et calcul des phénomènes induits dans le corps humain par des champs électromagnétiques de fréquence inférieure au. Available online: https://theses.hal.science/tel-00179791v1/document (accessed on 10 January 2024)
68. Ren, Z.; Razek, A. A Coupled Electromagnetic-Mechanical Model for Thin Conductive Plate Deflection Analysis. *IEEE Trans. Magn.* **1990**, *26*, 1650–1652. [CrossRef]
69. Freschi, F.; Giaccone, L.; Cirimele, V.; Canova, A. Numerical Assessment of Low-Frequency Dosimetry from Sampled Magnetic Fields. *Phys. Med. Biol.* **2018**, *63*, 015029. [CrossRef]
70. Li, C.; Ren, Z.; Razek, A. An Approach to Adaptive Mesh Refinement for Three-Dimensional Eddy-Current Computations. *IEEE Trans. Magn*. **1994**, *30*, 113–117. [CrossRef]
71. Piriou, F.; Razek, A. Calculation of Saturated Inductances for Numerical Simulation of Synchronous Machines. *IEEE Trans. Magn.* **1983**, *19*, 2628–2631. [CrossRef]
72. Madani, S.S.; Schaltz, E.; Kær, S.K. Thermal Analysis of Cold Plate with Different Configurations for Thermal Management of a Lithium-Ion Battery. *Batteries* **2020**, *6*, 17. [CrossRef]
73. Gabriel, S.; Lau R.W.; Gabriel, C. The Dielectric Properties of Biological Tissues: II. Measurements in the Frequency Range 10 Hz to 20 GHz. *Phys. Med. Biol.* **1996**, *41*, 2251–2269. [CrossRef]
74. Barchanski, A.; Steiner, T.; De Gersem, H.; Clemens, M.; Weiland, T. Local Grid Refinement for Low-Frequency Current Computations in 3-D Human Anatomy Models. *IEEE Trans. Magn.* **2006**, *42*, 1371–1374. [CrossRef]
75. Hasgall, P.; Neufeld, E.; Gosselin, M.C.; Kingenböck, A.; Kuster, N.; Hasgall, P.; Gosselin, M. IT'IS Database for Thermal and Electromagnetic Parameters of Biological Tissues. 2012. Available online: https://www.scienceopen.com/document?vid=a95fbaa4-efd8-429a-a59e-5e208fea2e45 (accessed on 1 November 2023).
76. Makarov, S.N.; Noetscher, G.M.; Yanamadala, J.; Piazza, M.W.; Louie, S.; Prokop, A.; Nazarian, A.; Nummenmaa, A. Virtual Human Models for Electromagnetic Studies and Their Applications. *IEEE Rev. Biomed. Eng.* **2017**, *10*, 95–121. [CrossRef]
77. Yang, Y.; Zeng, S.; Li, X.; Hu, Z.; Zheng, J. Ultrahigh and Tunable Electromagnetic Interference Shielding Performance of PVDF Composite Induced by Nano-Micro Cellular Structure. *Polymers* **2022**, *14*, 234. [CrossRef]
78. Yao, B.; Hong, W.; Chen, T.; Han, Z.; Xu, X.; Hu, R.; Hao, J.; Li, C.; Li, H.; Perini, S.E. et al. Highly Stretchable Polymer Composite with Strain-Enhanced Electromagnetic Interference Shielding Effectiveness. *Adv. Mater.* **2020**, *32,* 1907499. [CrossRef]
79. Yun, T.; Kim, H.; Iqbal, A.; Cho, Y.S.; Lee, G.S.; Kim, M.-K.; Kim, S.J.; Kim, D.; Gogotsi, Y.; Kim, S.O. et al. Electromagnetic Shielding of Monolayer MXene Assemblies. *Adv. Mater.* **2020**, *32,* 1906769. [CrossRef]
80. Cheng, J.; Li, C.; Xiong, Y.; Zhang, H.; Raza, H.; Ullah, S.; Wu, J.; Zheng G.P.; Cao, Q.; Zhang, D., et al. Recent Advances in Design Strategies and Multifunctionality of Flexible Electromagnetic Interference Shielding Materials. *Nano-Micro Letters* **2022**, *14*, 80. [CrossRef]
81. Mohammad, M.; Wodajo, E.T.; Choi, S.; Elbuluk, M.E. Modeling and Design of Passive Shield to Limit EMF Emission and Minimize Shield Loss in Unipolar Wireless Charging System for EV. *IEEE Trans. Power Electron.* **2019**,*12*, 12235–12245. [CrossRef]
82. Canova, A.; Corti, F.; Laudani, A.; Lozito, G.M.; Quercio, M. Innovative Shielding Technique for Wireless Power Transfer Systems. *IET Power Electron*. **2023**, 1–8. [CrossRef]
83. Zang, Z.; Guo, Z.; Fan, X.; Han, M.; Du, A.; Xu., W.; Ouyang, Z. Assessing the Performance of the Pilot National Parks in China. *Ecol. Indic.* **2022**, *145*, 109699. [CrossRef]
84. Díaz, S.; Settele, J.; Brondízio, E.S.; Ngo, H.T.; Agard, J; Arneth, A.; Balvanera, P.; Brauman, K.A.; Butchart, S.h.m.; Chan, K.M.A. et al. Pervasive Human-Driven Decline of Life on Earth Points to the Need for Transformative Change. *Science* **2019**, *366*, 6471. [CrossRef]
85. Coad, A.; Nightingale, P.; Stilgoe, J.; Vezzani, A. Editorial: The Dark Side of Innovation. *Ind. Innov.* **2021**, *28*, 102–112. [CrossRef]
86. Kruželák, J.; Kvasničáková, A.; Ušák, E.; Ušáková, M.; Dosoudil, R.; Hudec, I. Rubber Magnets Based On Nbr And Lithium Ferrite With the Ability to Absorb Electromagnetic Radiation. *Polym. Adv. Technol*. **2020**, *31*, 1624–1633. [CrossRef]
87. Qin, M.; Zhang, L.; Wu, H. Dielectric Loss Mechanism in Electromagnetic Wave Absorbing Materials. *Adv. Sci.* **2022**, *9*, 2105553. [CrossRef]
88. Ilmiawati, A.; Falestin, M.; Maddu, A. Films from PVA and Sansevieria trifasciata Leaves Extracts as a Smartphone Protector with Radiation Reducing Property and Its LC-MS Analysis. *Indonesian J. Chem.* **2023**, *23*, 594. [CrossRef]
89. Razek, A. Strategies for Managing Models Regarding Environmental Confidence and Complexity Involved in Intelligent Control of Energy Systems—a Review. *Adv. Environ. Energies* **2023**, *2*, 1–16. [CrossRef]
90. Monteiro, J.; Pedro, A.; Silva, A.J. A Gray Code model for the Encoding of Grid Cells in the Entorhinal Cortex. *Neural Comput 10/12 Appl.* **2022**, *34*, 2287–2306. [CrossRef]

91. Wang, F.; Tian, D. On Deep Learning-Based Bias Correction and Downscaling of Multiple Climate Models Simulations. *Clim. Dyn.* **2022**, *59*, 3451–3468. [CrossRef]
92. Brassey, C.A.; Behnsen, J.; Gardiner, J.D. Postcopulatory Sexual Selection and the Evolution of Shape Complexity in the Carnivoran Baculum. *Proc. R. Soc.* **2020**, *287*, 20201883. [CrossRef]
93. Pendergraft, J.G.; Carter, D.R.; Tseng, S.; Landon L.B.; Slack K.J.; Shuffler M.L. Learning from the Past to Advance the Future: the Adaptation and Resilience of NASA's Spaceflight Multiteam Systems Across Four Eras of Spaceflight. *Front Psychol.* **2019**, *10*, 1633. [CrossRef]
94. Amanatidis, G.; Aziz, H.; Birmpas, G.; Filos-Ratsikas, A.; Li, B.; Moulin, H.; Voudouris, A.A.; Wu, X.W. Fair Division of Indivisible Goods: Recent Progress and Open Questions. *Artif Intell.* **2023**, *322*, 103965. [CrossRef]
95. Meta-Learning in Games. Available online: https://arxiv.org/abs/2209.14110 (accessed on 10 January 2024).
96. Esposito, G.; Terlizzi, A. Governing Wickedness in Megaprojects: Discursive and Institutional Perspectives. *Policy Soc.* **2023**, *42*, 131–147. [CrossRef]
97. Zonneveld, K.A.F.; Harper, K.; Klügel, K.; Chen, A.; Lange, L.; Versteegh, M. Climate Change, Society, and Pandemic Disease in Roman Italy Between 200 BCE and 600 CE. *Sci. Adv.* **2024**, *19*, 4. [CrossRef]

Copyright © 2024 by the author(s). Published by UK Scientific Publishing Limited. This is an open access article under the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Publisher's Note: The views, opinions, and information presented in all publications are the sole responsibility of the respective authors and contributors, and do not necessarily reflect the views of UK Scientific Publishing Limited and/or its editors. UK Scientific Publishing Limited and/or its editors hereby disclaim any liability for any harm or damage to individuals or property arising from the implementation of ideas, methods, instructions, or products mentioned in the content.