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Risks and Benefits of Electromagnetic Fields Interacting with Plant Cell Biology at Lower to Higher Frequencies

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K E Y W O R D S

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A B S T R A C T

The number of people exposed to electromagnetic fields (EMFs) created by humans has risen greatly since the 1920s when regular radio transmissions began. Today, we are constantly bombarded by EMFs of all kinds, most prominently from communication and security gadgets. Knowing how plants and other systems are affected by EMFs is crucial for both public health and technological development. Furthermore, cell membrane activity such as potassium and sodium ions conductivity, transmembrane potentials, non-selective channels and even the cell cycle have all been proven to be affected by EMFs. Terahertz (1015-1020 Hz), millimetre waves (115-1015 Hz) and radiofrequency waves (100-115 Hz) are discussed in this work, along with their effects on plants. Millimeter and terahertz radiation are given special consideration because of the rising popularity of these frequencies and the consequent rise in plant growth and yield. The active transport across the cytoplasmic membrane may be disrupted by mild electromagnetic waves, and terahertz radiation has been shown to interact with DNA and cause genetic instability. Experiments are needed to resolve some seeming inconsistencies, such as the fact that radiation can stimulate or stunt plant development. Also, the present review sheds light on the possible effects of EMFs on honey bee production, the amphibian environment and on insect ecosystems.

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1. Introduction

Wireless communication has quickly come to be seen as a great technological advance, even though it was invented at the tail end of the nineteenth century. It's hard to imagine modern living without the plethora of wirelessly connected mobile devices. Wireless communication is a popular and rapidly evolving technology. Radio-frequency, electromagnetic fields (EMFs) are mostly used to power wireless networks and personal gadgets. Mobile phones transmit radio waves via a base station network, which consists of a set of permanently installed antennas. Existing networks employ frequencies between 6 GHz to 0.1 GHz (Mokhtari et al., 2023), whereas cutting-edge devices have been spotted using much higher frequencies (300 MHz to 3 GHz, with 1m to 10cm wavelength). The EMFs produced by Wi-Fi, mobile phones, and other connected devices are becoming increasingly ubiquitous in the environment. These EMFs can penetrate dielectric materials and result in dielectric heating (Maksymych et al., 2023). Living material quickly interferes with EMFs due to its poor dielectric properties. This dielectric heating can occur in any living organism, even in insects. This interference depends on several factors, including (but not limited to), the EMF's amplitude and frequency, a general form of the material, and the tissue's conductivity. Hence, EMFs have immediate and long-term consequences on practically every system, including the environment (Jocqu et al., 2023).

The effects of EMFs on organisms other than humans have been studied using animal and plant models since at least the 1930s (Levitt et al., 2022). Plants, yeast cells, nematodes, insects, amphibians, non-human primates, pigs, chickens, cats, dogs, rabbits, and different microorganisms have all been used in a study, while mice and rats have been the most common (Seyedmousavi et al., 2022). Exhaustion, anaemia, internal bleeding, vomiting, diarrhoea, and death may all result from ingesting a toxic quantity of radiation. Exposure at high levels may also permanently damage cellular DNA, which may increase the risk of cancer (Prosser CL et al., 1947; Møller et al., 2013). Figure 1 provides a high-level explanation of brain injury in humans. There is a wide range of exposure levels, frequencies, and other factors that influence every species. There are different effects on living beings and their habitats caused by the various frequencies used in today's technology, from the very low to the very high (Gondal et al., 2023). Microwaves, megahertz, and terahertz all have effects on plants; some experts think these are beneficial to the plants to varying degrees, while others argue they are harmful to the plants and food chain. To find a solution to this seeming conflict, more study is required.

Most research on radiation's impact on plants has been done in a lab or other controlled environment (Caplin and Willey et al., 2018). It is

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common practice to expose seeds or young plants to a powerful EMF source, often cobalt-60, and then compare them to controls that were not exposed to the EMFs (Marcu et al., 2013). Researchers have found that while modest doses can stimulate growth, high doses can have harmful effects. Although some extinction events throughout the ages have been attributed to extremely rare gamma-ray bursts associated with supernova implosions, the radiation doses utilized in medical radiation therapy are quite high (usually 50-300 HZ) (Maity et al., 2013). Also, most studies only use acute, high-dose-rate gamma-ray exposure, so their results may not generalize to issues about the effects of radionuclides in soil from either natural or anthropogenic sources (Thorsett et al.,1995). Multigenerational exposure at low dosage rates is the norm. Chronic dosages of radiation in space are maybe even different than those received by gamma rays. More research is required to establish the potential impacts of higher EMFs on plant physiology, such as cellular effects, membranous effects, and transportation effects.
It has been found that millimetre-wave irradiation has dynamic effects on organisms; this technology is ecologically sound because of its long wavelengths and little risk to human health. Many microbes' metabolic processes, cell division, enzyme production, and biomass buildup are all affected by this (Vander et al., 2013). Millimetre-wave-treated wheat seeds produced taller plants with greater biological harvest yields than untreated seeds. Nevertheless, irradiation with millimetre waves showed no beneficial effect on potato development. Soybeans, on the other hand, have not been studied to see whether millimetre-wave irradiation has any influence on harvesting (Zhong et al., 2020). Higher frequencies and newer, more specific signal characteristics/waveforms are at the heart of 5G's promise (Levitt et al., 2022), which have the potential to affect plants, insects, and marine life in particular and have far-reaching consequences for the ecosystem as a whole, rising EMF levels found in ambient contexts undoubtedly heighten concerns. 5G is becoming increasingly popular as a network platform, despite our incomplete understanding of its interactions with the larger architecture of 3-4G long term evolution (LTE) networks. Both the characteristics of 5G itself and its surrounding environment make it stand out from the norm. More research is needed to determine the full extent of the dangers presented by terahertz and gigahertz sensations to wheat and other crops. Additional research is required in order to identify the full extent of the dangers that terahertz and gigahertz sensations pose to medicinal plants, herbs, and other plants that give protection from pollution. Several factors, including plant species, climate, site-specific environment, movement and variation, genetic diversity, and orientation towards the field make it difficult to quantify extrapolations of plants from highly controlled laboratory circumstances.
This chapter highlights the long and short-term effects of EMFs on humans, plants, animals and on other organisms. Also, the review sheds light on how lower to higher hertz frequency EMFs effects plant morphology, physiology and ecosystems. There is a correlation between the results of controlled research and those of field observations of plants. When this holds, it's easier to feel certain. Yet, the consequences of pants are not always positive; sometimes whole species vanish. Yet, studies extrapolating to field exposure have demonstrated damage to several species in the vicinity of communication infrastructure.

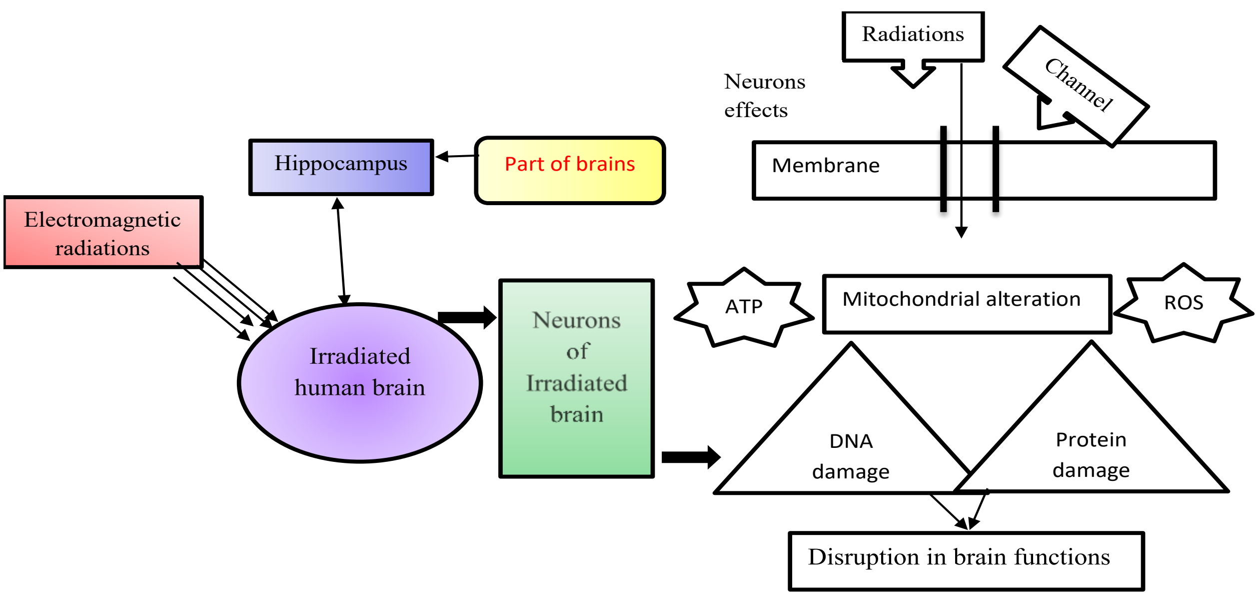

Figure 1 Different types of radiation affect the human body including the brain. Brain dysfunction and decreases in spatial memory are the results of microwave radiation's effects on proteins in neurons, on mitochondrial activity via modifications to ROS and ATP production, and on single- and double-stranded DNA breaks. The figure presented in this manuscript has been reproduced, modified and the few contents were copied from the source Mumtaz et al. (2022).

1.1. Effects

Long and short-term effects have been observed on human and animals' health and are discussed below. Human and animal exposure throughout the short and long term is not yet a topic that has received sufficient attention. A small number of research were done by scientists using ionizing radiation, non-ionizing radiation, and other frequencies and methods. Until we know for sure what frequency ranges are harmful to humans and animals, we can't add them.

1.1.1. Short-term effects on humans and animals

In today's modern world, use of mobile phone is very common and it has short- and long-term exposure to humans. Under both headings, radiation exposure to humans from certain frequency has been discussed. People who use their phones for more than 50 minutes a day are at risk for thermal damage to the brain caused by the breakdown of glucose, according to findings from the International Commission for the Non-Ionization of Radiation Protection (Moradi et al., 2016). Tissue heating in case of human is the primary mechanism through which radiofrequency energy affects living organisms. The brain and other interior organs receive essentially no temperature increase since most of a cell phone's radiation is absorbed by the skin and other external tissues. Several studies have looked into how exposure to radiofrequency fields affects things like electrical activity in the brain and memory, a person's ability to sleep, and even their heart rate and blood pressure. Exposure to radiofrequency fields has been studied extensively, but no negative health consequences have been consistently reported below the threshold at which tissue heating occurs. Electromagnetic hypersensitivity refers to a subjective reaction to EMFs, however, studies have failed to find a causal link between exposure and self-reported symptoms.

1.1.2. Long-term effects on humans and animals

Most epidemiological studies of the long-term dangers of radiofrequency radiation have focused on the possible link between mobile phone use and brain tumours. However, there is no evidence from animal research that long-term exposure to radiofrequency fields increases cancer risk (Aly et al., 2008). Several large-scale, worldwide epidemiological studies exploring a variety of health endpoints in adults have either been completed or are underway. Interphone, led by the International Agency for Research on Cancer (IARC), is the largest case-control study ever conducted on people looking into potential links between mobile phone use and head and neck malignancies.

No higher risk of glioma or meningioma was detected in the international pooled analysis of data from 13 participating nations with mobile phone use for more than 10 years. However, there was no clear pattern showing an increased risk with greater duration of use, and there was no evidence that people in the top 10% of cumulative mobile phone use were at elevated risk of glioma. The researchers determined that the reliability of these findings and the possibility of drawing a causal relationship were compromised by biases and inaccuracies (Rashid and Song, 2019).

1.2. Radiations working ways

Before analyzing radiation's effects on vegetation, it is crucial to have a firm grasp of what radiation is and how it interacts with matter. The Sun isn't the only thing that emits radiation; mobile phones and televisions do, too. It's not always bad to be around radiation. Depending on the type of radiation and the duration of exposure, it may be quite harmful. Ionizing radiation with a high enough energy level can kill living creatures. Radiation can be utilized to convey energy via particles or waves. Negative effects on individual species were seen at radiation dosages between 5 and 400 rad/year, showing that ecological masking occurred. Exposure levels greater than 400 rad annually were harmful to communities and populations. Because of this, it may interact with an atom and alter the atomic charge. In extreme cases, this could lead to nuclear damage, which could alter DNA. Furthermore, radiation causes significantly more mutations. Previous research has indicated that some plant species, but not all, experience elevated mutation rates (Figure 2). Mutations can be detrimental if the DNA of a living organism has been tampered with. Plants in the neighborhood of a reactor could be harmed even if they don't come into contact with radioactive chemicals or radiation (Slovic, 1996).

1.2.1. Possible sources of radiation

The EMF radiates energy and momentum as it travels across space as electromagnetic radiation (EMR). The gamma rays, X-rays, ultraviolet light, regular light, infrared light, microwaves, visible light, ultraviolet, and radio waves are all direct or indirect examples of EMR that are linked to EMFs. Effects and benefits of millimetre waves on plant growth

Empirical evidence suggests that a wide variety of agricultural products exhibit dielectric characteristics (Peplinski et al., 1995). At both workplace and public exposure levels, the monetary value of the specific absorption rate (SAR) at 2.4 GHz has been determined. The research found that when fruit shape-shifted from spherical to more accurate, the SAR value of plants increased substantially, largely as a result of the decreased mass of the latter. Hence, the rate at which the plant body absorbs energy is affected by differences in plant structure and shifts in the biological composition of plant tissues. Scientists in Nizhny Novgorod argue that ionizing radiation harms living things by disrupting their physiological processes.

Millimeter-wave EMFs have developed as a unique and pervasive environmental element due to their application in remote sensing, radar, radiometry and satellite communication technologies. Increased early pollen-tube emergence, shoot multiplication, leaf weight and seedling length were all affected by millimetre-wave irradiation that contributes to plant development (Peplinski et al., 1995). A study has been conducted to look at what happens to soybean seedlings when they are exposed to millimetre-wave radiation. Plants benefit from chaperonin 10's involvement in maintaining appropriate protein structure and cellular homeostasis, which is notably important for the assembly of ribulose bisphosphate carboxylase oxygenase. In cold conditions, aberrant mitochondrial metabolism was seen in soybean with decreased chaperonin expression. Millimetre-wave irradiation has been shown to have a regulatory effect on plant development, as shown by the present results and earlier research. There is a large body of research showing that millimetre-wave irradiation is beneficial to plant development, but less is known about its impact when plants are subjected to abiotic stress. Many crops are vulnerable to severe abiotic stress caused by flooding. After germination, if the plant is flooded, the root tip will die and lateral root growth will be severely stunted. Soybean long-term growth and production might benefit greatly from increasing flooding tolerance now. While many methods have been used to improve soybeans' flood tolerance, a straightforward and secure method is required. Once the water was removed, the soybeans' root and hypocotyl lengths returned to normal, indicating that millimetre-wave irradiation stimulated their development despite the stress of flooding. Results of various studies showed that millimetre-wave irradiation is critical for soybean root development. Soybean production went up because of the plant's better resilience to waterlogging thanks to stronger root development after periods of flooding stress. Approximately 50 chilli plants exposed to millimetre radiation from seeds to maturity developed larger, more leaves than their control group peers. According to the study's leader, Bhaskar Gupta, a professor of electronics and communications at Jadavpur University, the test plants' leaves were wrinkled and appeared dull compared to regular plants (Panagariya et al., 2023).

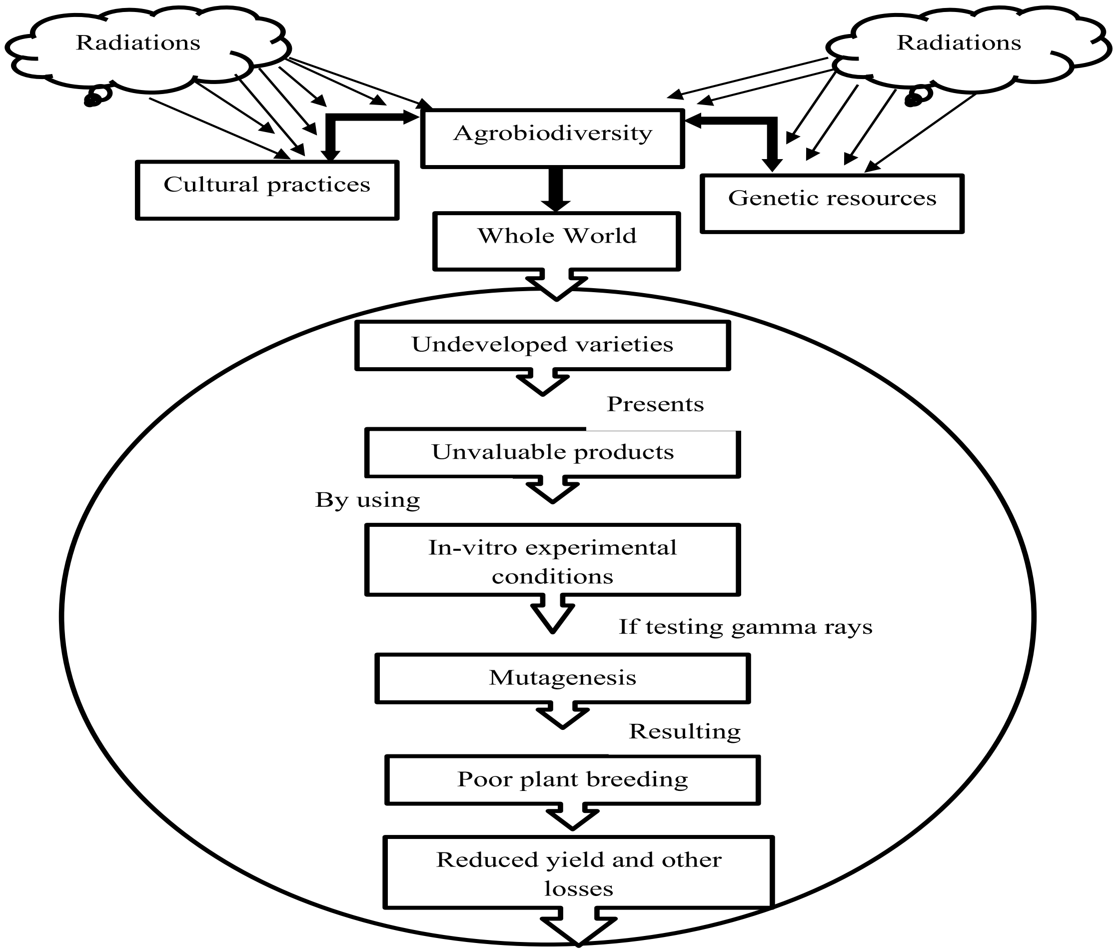

Figure 2 Negative impacts of radiations on agrobiodiversity especially causing mutation. The figure in this manuscript was regenerated, modified and the few contents were copied from the source: Asaari et al. (2018).

1.2.2. Carbohydrate metabolism and millimetre waves

During the germination stage, plants make the transition from anaerobic to aerobic respiration. During germination, a rise in reactive oxygen species production inhibits several glycolytic enzymes. Previous research found that the abundance of pyruvate kinase, enolase, and glyceraldehyde-3-phosphate dehydrogenase reduced during growth in unirradiated soybeans but did not alter during growth in irradiated soybeans (Zhong et al., 2020). Phospho-hexokinase levels went down in both irradiated and unirradiated soybeans, despite these shifts. Immunoblot analysis showed no discernible differences between unflooded soybeans treated with different irradiation levels. It was shown that irradiating soybeans with millimetre waves increased glycolysis, but this regulatory impact could be blocked by a rate-limiting step farther upstream (Chung et al., 2010).

Soybean roots were unable to convert ADP to ATP by oxidative phosphorylation after being flooded, their carbohydrate metabolism was disrupted (Finneganet al., 2012) and ADP to ATP phosphorylation was dominated at the substrate level. Thus, a major adaptation of plants to flooding stress is a change in sugar metabolism, namely in its downstream glycolysis. To cope with oxygen deprivation caused by floods, the species or genotype with the highest glucose content in its roots and the most effective metabolic mechanism connected with carbohydrate mobilization and fermentation route would be preferable.

1.2.3. Millimeter waves and oxidative stress

The primary detoxifying pathway for active oxygen species in plant cells is the metabolism of ascorbate and glutathione. The ascorbate-glutathione cycle is crucial in several stages of development in addition to its function in mitigating oxidative stress. In most of the previous research, the existence of GR and the patterns of change were identical across unflooded and flooded situations, regardless of whether the soybeans had been irradiated or not (Willis et al., 2022). They concluded that oxidative stress induced significant changes in plant growth and development.

The effects of EMR from mobile phones operating at 1800MHz on the germination, root development, and mitotic division of root tips of Lens culinaris were studied by Akbal et al. (Akbalet al.,2012). In the conditions tested, they found that oxidative stress in the form of dormant seeds did not impact germination, but did slow root development. Mitosis rates increased significantly, notably in the resting seeds. Possible causes of this increase include faulty spindle formation. Furthermore, Kumar et al. (Kumar et al., 2016) observed significant changes in starch and sucrose metabolism when plants were exposed to 1800 MHz EMR. It might be due to the stress induced by EMFs. Sharma et al. (2023) studied the effects of 900 MHz EMR on genotoxicity and oxidative stress utilizing the Trigonella foenum-graecum assay system. They concluded the negative effects of EMR utilization towards plant species. Similarly, Gustavino et al. (2016) and Gustavino et al. (2014) 915 MHz frequency radiation to determine the effects on the root tips of Vicia Faba. Results of these suggest that radiations have negative consequences on the root tips of Vicia Faba due to certain reasons oxidative stresses that are completely unknown and must be determined on a priority basis to overcome the contradictions and better understanding.

1.3.Mechanism of action

During typical oxidative reactions, all aerobic organisms produce reactive oxygen species (ROS). The stimulation of host defence genes and cellular signaling relies on ROS, which is non-toxic at low concentrations. Yet, ROS levels rise dramatically amid environmental exposures like ultraviolet radiation (UVR), leading to oxidative stress. Depletion of the ozone layer has increased UV-B radiation reaching Earth's surface in recent decades due to the production of human atmospheric pollutants such as chlorofluorocarbons, organobromides, chlorocarbons, and reactive nitrogen species (RNS) (Pathak et al., 2019). Lipidomic peroxidation, the breakdown of endogenous lipid-soluble antioxidants, and changes in gene expression are all effects of reactive oxygen species (ROS) on plants. Both free radicals (per hydroxy, HO; alkoxy, RO; superoxide, O_2; hydroxyl, OH) and non-radicals (nitrous oxide, O_2) are included in the ROS (singlet oxygen, $^1O_2$ and hydrogen peroxide, H_2O_2). Photosystems II and I (PSII and PSI) in chloroplasts are the primary locations for $^1O_2$ and O_2 generation (Asada et al.,2016). The ubiquinone, complex III and complex I of the mitochondrial electron transport chain are the primary sites for O_2 production (Liu et al., 2002). Plants possess very efficient enzymatic (glutathione S-transferase, guaiacol peroxidase, glutathione peroxidase, dehydroascorbate reductase, monodehydroascorbate reductase, glutathione reductase, ascorbate peroxidase, catalase, and superoxide dismutase), and non-enzymatic (α-tocopherols, alkaloids, phenolic compounds, glutathione and ascorbic acid) and antioxidant defence systems which protect plant cells from oxidative damage by scavenging of ROS. The production of ROS by plants when exposed to EMFs, as well as the many enzymatic and non-enzymatic antioxidant defence mechanisms used by plants for protection must be discussed for better understanding.

1.3.1. Megahertz radiations and metabolism of plants

Several studies show that subjecting plants to high frequency electromagnetic fields causes an increment in the synthesis of malondialdehyde (MDA) which is known as a membrane modification marker) and activation of ROS metabolism (Zare et al., 2015; Singh etal.,2012). It is believed that transmission pathways enabling particular responses are established by ROS metabolism and activation of Membrane alteration. Plants' responses such as changes in pin2 gene, lecdpk-1, and calm-n6 expression to EMF exposure variate when cultivated in a high-calcium environment or grown with calcium responding mediators' chelators (EGTA) and channel blocker ($LaCl_3$), demonstrating the central role of calcium as a crucial second messenger in plants. Moreover, calcium is important in developing the plant response, since at least two calcium-related products (including calmodulin and calcium protein kinase) are involved in early gene expression in response to EMF exposure. There is an energy cost associated with this reaction as well; ATP levels and adenylate energy charge (AEC), both decline significantly (30%) after HF-EMF exposure (Roux et al., 2008). At this time, it is unclear whether the decreased AEC was caused by a rise in ATP consumption due to increased metabolic activity or by a decrease in AEC due to passive ATP departure via changed membranes. It is widely established that reduced AEC levels transform the catabolic enzyme pathways into an active state. Nevertheless, plant responses to EMF exposure were eliminated when ATP production was blocked with the decoupling agent carbonyl cyanide m-chlorophenyl hydrazone (CCCP) (Asada et al., 2006). Another signaling molecule directly linked to the effect of the environment on plants is nitric oxide (NO). Rapid upregulation of NO occurs in response to several stimuli, including drought stress or wounding. Recently, Chen et al. (2009) showed that wheat caryopses exposed to high strength 2.45 GHz EMF for 10 s resulted in enhanced activity of nitric oxide synthase and buildup of NO. Similar results were found by Qiu et al. (Qiu et al., 2013) in wheat, where they demonstrated that the NO scavenger carboxy-PTIO completely reversed the microwave pretreatment-induced cadmium tolerance. These findings support the hypothesis that NO synthase is induced by electromagnetic fields. High-power electromagnetic fields (a modified microwave oven) were utilized in these tests, therefore it's possible that a rise in sample temperature was responsible for the observed elevation in NO. To the best of our knowledge, low power (nonthermal) EMF exposure has not been linked to NO involvement. The increase of stress-related genes is a typical response (abscisic (ABA), jasmonic (JA) acids and tomato mutants) when entire plants are subjected to EMF (Beaubois et al., 2007). In contrast, following local exposure, the entire plant responds relatively quickly at a distance in the wild, but this response is disrupted in ABA, and in JL-5 mutants, suggesting the presence of a transmitted signal (whose transmission or origin is reliant on JA and ABA). Although the exact nature of this signaling is still a mystery, new research has shown that membrane potential may change following exposure to EMF. The fact that HF-EMF is a genuine component of the surrounding environment raises the fascinating prospect that the message being transmitted is made up of electrical impulses (either action potential or variation potential).

1.3.2. Changes in enzymatic activities

The ascorbate peroxidase, catalase, superoxide dismutase, and peroxidase enzyme activity all increased by a factor of two to four. Whether or whether this is due to the direct impact of EMF on live tissue is still up for debate. EMFs at these frequencies carry so little energy that they are not ionizing. Increased ROS metabolism has been linked to negative outcomes such as increased H_2O_2 generation, MDA elevations, and protein degradation. Increases in polyphenol oxidase and phenylalanine ammonia-lyase may indicate stress reactions associated with greater lignification, a common response of plants to environmental stress (Ngadze et al., 2012). Vigna (Abuet al., 2005), Phaseolus (Pinto et al., 1999), and Triticum (Kumar et al., 2020) all have lower protein content. It is unclear if the drop in protein content is from an increase in protein degradation and/or a decrease in protein synthesis, however, evidence shows that mRNA selection from translation occurs after plant exposure to HF-EMF (Vian et al., 2016). This may be a really interesting research topic. Hydrolytic enzymatic activities (amylases and invertases) responsible for the production of soluble sugar increase as the phosphorolytic and perhaps reversible starch phosphorylase activity decreases in sprouting seeds (Kaur et al., 2002). However, unlike seeds, mature leaves of the plant Plectranthus (Lamiaceae) respond differently to HF-EMF exposure, with a drop in soluble sugar occurring after exposure to 900 MHz EMF. This may be related to a suppression of the Krebs cycle and the pentose phosphate pathway. Classical responses of plants to environmental challenges include the buildup of proline, documented by various authors, as well as a rise in terpenoid emission and content in fragrant plants.

1.3.3. Gene expressions modifications

Although several studies have looked at how exposure to EMF affects enzyme activity, very few have looked at how it affects gene expression. Several repeatable alterations in 2D gel electrophoresis profiles were reported by Tafforeau et al. (Tafforeau et al., 2004) using a Gunn generator, indicating that gene expression is likely to be affected by the exposure treatment. While the findings of Jangid et al. (Jangid et al., 2010) provide indirect evidence that high-power microwave irradiation modifies gene expression in Vigna aconitifolia, therefore they don't completely rule out the idea of a thermal influence of microwave treatment. In suspension-cultured cells of the plant Arabidopsis thaliana, a microarray study (Engelmann et al., 2008) showed differential expression of numerous genes between the exposed and control (unexposed) conditions. They are, in general, turned down. The authors conclude that HF-EMF does not affect plant gene expression, however, they do point out that the significance of random fluctuations is mitigated by the p-value for RT-PCR. The altered expression of at least 5 stress-related genes in 3-week-old tomatoes subjected to HF-EMF in magnetic selective ride control for only 10 minutes at 900 MHz and 5 Vm-1 demonstrates that whole plants are more sensitive to HF-EMF than cultured cells. Using a significantly longer exposure duration and a lot less sophisticated exposure setup, Rammal et al. (2014) independently replicated these findings (cell phone). Plants often exhibit a two-stage response to stress (Vian et al., 1999): an initial, rapid increase in transcript accumulation that lasts 15-30 min, followed by a second, greater increase from the initial baseline level after 60 min. This pattern was seen in tomatoes exposed to EMF, and it prompted us to examine the role of the early and late population of transcripts by measuring their association with polysomes in the plant's physiological processes (which reflects their putative translation to proteins). We have previously demonstrated (Roux et al., 2008) that the early mRNA population (0-15 min) has a weak connection with polysomes and is thus poorly translated, while the late mRNA population (60 min) has a robust connection with polysomes. Only the late mRNA population is translated into proteins, suggesting that this observation may have important physiological implications. Instead, genetic alteration has been documented in plants in response to variations in radiation source, frequency, and angle of incidence (Guimarães et al., 2018). Figure 3 provides a similar summary of radiation's impact on genetic modification by demonstrating how a shift in the angle of incidence from one radiation source to another can disrupt many processes.

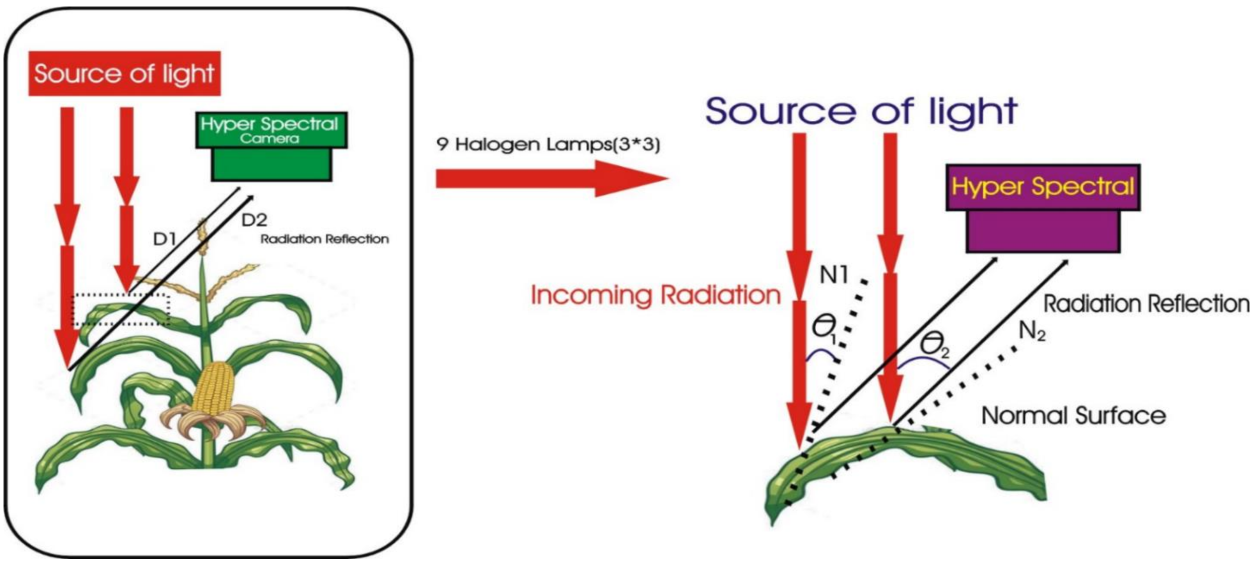

Figure 3 Genetic changes induced by radiation. Figure has been reproduced for the present manuscript and only few contents were copied from the source (Riviello-Flores et al., 2022).

1.4. Plant level

Plants exposed to EMF undergo the biochemical and molecular changes outlined above, which may lead to morphogenetic abnormalities in plant development. The effects of HF-EMF on plant development are being documented in an increasing number of studies. Increases in radish and tomato plant height and photosynthetic surface area (Radzevičius et al., 2013) and tobacco seedling roots have been seen after exposure to ultrashort pulsed high-power EMF. There may be a connection between the underlying difference in physical characteristics of pulsed electromagnetic field and HF-EMF and the resulting differential impacts on plant life. In most cases, exposure to HF-EMF had the same effect on seedlings or plants as it did on seeds. Researchers Singh et al. (2012) found that cell phone radiation has a profound effect on mung bean rhizogenesis (root quantity and length), probably by activating multiple stress-related enzymes (peroxidases and polyphenol oxidases). Lens culinaris seedlings treated while dormant to electromagnetic fields at 1800 MHz had their root development inhibited by over 60%, as shown by research by Akbal et al. (2012). All three of these reactions an uptick in ROS-related enzymes, lipid peroxidation, and proline accumulation are typical of plant responses to stressful circumstances and were reported simultaneously by these scientists. Surducan et al. (2013) also discovered that exposing bean and maize seedlings to EMF accelerated their development. The effects of EMF radiation on the instantaneous development of parrot feathers were investigated by Senavirathna et al. (2014) employing nanometer-scale elongation rate changes. These authors showed that plants subjected to EMFs had decreased fluctuation rates that persisted for several hours after exposure, providing strong evidence that the plants' metabolisms were stressed during this time. It's important to note that the exposure did not result in any warming of the plant (as measured using sensitive thermal imaging). Following HF-EMF exposure, plants exhibited a variety of morphological changes, including the induction of epidermal meristems in flax, the abscission of flower buds, an increase in the number of nitrogen-fixation nodules in leguminous, and the delayed, reduced growth of the secondary axis in Rosa.

Exposure of 12-day-old maize seedlings to 0.47 W kg^{-1} GHz EMF causes a loss in photosynthetic pigment content; in particular, the chlorophyll concentration drops by 80% after 7 hours of exposure, suggesting that this decrease in growth may be attributed to a decreased photosynthetic potential. Exposure of maize seedlings to microwave radiation decreased their levels of chlorophyll a and b, as shown by the research of Ursache et al. (2009). Hamada (2007) also discovered that exposing caryopses to 10.5 GHz for 75 minutes reduced the amount of chlorophyll in seedlings 14 days old. After 4 hours of exposure to 1800 MHz (332 mW m^2), Kumar et al. (2020) found that total chlorophyll in maize seedlings decreased by 13%. Abnormal photosynthetic activity, which depends on numerous factors such as chlorophyll and carotenoid levels, may be linked to these alterations. Exposure of duckweeds to EMF at 2-8 GHz and 45-50 Vm^{-1} generated alterations in the nonphotosynthetic quenching, suggesting a possible stressed situation, as shown by various researcher.

1.4.1. Megahertz radiations and plant reproduction

Reproduction of plants may be reduced due to the effects of ionizing radiation on their reproductive organs and gametes. Reproduction and phenology may be pushed back as a result. Radiation may also influence the disparity between the number of buds and the number of flowers, with a higher number of flowers indicating a later time of reproduction if compared to a smaller number of buds. Plant development may be inhibited by radiation, resulting in fewer blossoms available to be pollinated. Reproductive output, including seed set, may be affected by the quantity and size of blooms. We have collected this data for 73 types of flowering plants at Chornobyl and Fukushima to see whether ionizing radiation affects plant development.

1.4.2. Plant growth and mild electromagnetic waves

Seeds of several species treated with elevated MF grew at faster rates than their untreated counterparts. The total fresh weight of the corn crop increased because the treated plants grew taller and heavier than the control plants. The best results came from consistently exposing plants to magnetic fields of 125 or 250 mT. Exposure of flowers to pollinators may be reduced if plant development is hindered by even modest levels of radiation. Reproductive output, including seed set, may be affected by both the quantity and size of blooms.

Effects of radiations on ecosystem model

EMR includes x-rays, gamma rays, and visible light because these types of radiation have electric and magnetic fields that change at the same time. Radiation from mobile phones and cell tower antennas is mostly caused by these, which are released by electrically charged particles. Birds, people, other animals, plants, and the environment all face significant risks from EMR. The ecosystem model includes birds, amphibians, plants, humans, honey bees and so on. Some of these have been discussed here. Previous research has shown that radiation can severely disrupt the reproductive system, but that its effects lessen over time in case of fishes, birds' mammals. This could be because the worst-affected families die out and the rest adapt. More field research of this kind is needed to confirm whether or not adaptation has taken place. The evolutionary principles of competition and selection take time to play out. There may be indications of evolution or adaptation in studies using Chernobyl samples.

1.4.3. Effects of electromagnetic radiations on birds

Some of the bird species most vulnerable to these radiations are sparrows, pigeons, parrots, and swans. These repercussions will be just as serious as those caused by any other kind of pollution. Birds lose their normal navigational abilities after being exposed to radiofrequency radiation because they become disorganized and fly in every direction at once. Birds' reproductive abilities are threatened by the neuronal damage and locomotory abnormalities that result from these radiations. By pinpointing the frequency and range of non-ionizing electromagnetic fields that are harmful to the environment, we can create mitigation strategies that allow for the safest, most beneficial use of wireless technology for everyone. Thus, lawmakers must approve tougher radiation regulations. Many studies examining the harmful effects of these radiations on birds, human health, and the environment have been reviewed, and novel solutions for remediation have been presented.

Birds' sensitivity to magnetic fields has long been documented. There is clear evidence that the proliferation of cell towers in urban areas is causing a decline in bird populations there. It has been determined that the microwaves (300 MHz to 300 GHz) emitted by mobile phone towers and phones are to blame for damaging sparrow eggs and embryos. The proliferation of cell phones and cell towers is proceeding without enough consideration of the obstacles it poses. Many throughout the globe are concerned about the health effects of radiation from portable electronic devices and cell towers. The results of the experiments show that EMR affected the growth of basil plants.

Several experts have speculated that variables related to environmental change may be to blame, although this is still very speculative. Most of the birds are insectivores and the fact that they have been discovered malnourished and confused points to a lack of food. Rapidly expanding flames are also suspected of having an impact on the survival of these birds. Birds, being at the pinnacle of the developed way of life, are also suitable indicators of the general health of our biota. Marine species are just as important as land-based ones for maintaining the planet's ecological balance. Every living thing on Earth fills a certain niche in the natural order of things and contributes something special to the ecosystem. Despite this, however, many animals and birds are becoming endangered nowadays.

The general public does not recognize the significance of the health risks posed by radiation from cell phones and cell towers. The cell company keeps checking to make sure there are no health risks. Although some countries have adopted radiation standards that are between one-hundredth and one-thousandth of these qualities based on their research, even international organizations like the World Health Organization, the International Commission on Non-Ionizing Radiation Protection, the Federal Communications Commission, and so on have not suggested stricter safe radiation rules. All researchers should become serious about finding new ways to keep the environment safe since maintaining plant diversity depends on having a wide range of bird species. In addition, pre-concentration and extraction methods have simplified, sped up, and reduced the cost of effectively concentrating and enhancing the target compound/s in complicated natural testing like wastewater and soil.

1.5. Effects of electromagnetic radiations on honey bees

Electropollution is a result of the increased use of electronic devices. As honeybees use magnetite in their bodies for navigation, electro-smog has harmed their biology and behaviour. There has been a reported collapse in honeybee numbers. The cause has not been determined. We have compared the productivity of honeybee colonies exposed to cellphone radiation with those that were not. The number of bees in a colony and the number of eggs produced by the queen have both decreased significantly. Foragers' behaviour was significantly impacted, and the colony ended up with no honey or pollen as a result of the exposure. The proliferation of electronic devices has resulted in widespread environmental electropollution. As honeybees use magnetite in their bodies for navigation, electro-smog has harmed their biology and behaviour. There has been a reported collapse in honeybee numbers. The cause has not been determined. Researchers studied the productivity of honeybee colonies that were or were not exposed to radiation from cell phones. Both the number of bees in the colony and the pace at which the queen laid eggs decreased significantly. Foragers' behaviour was significantly impacted, and the colony ended up with no honey or pollen as a result of the exposure.

1.6. Effects of electromagnetic radiations on insects

Insects often absorbed more RF power at and above 6 GHz than they did at lower frequencies. Our modelling revealed that there would be a 3-370% increase in absorbed power if only 10% of the incoming power density was moved to frequencies beyond 6 GHz.

Despite the common belief that radiofrequency radiation cannot directly harm DNA, genotoxic effects have been seen in terrestrial, aerial, aquatic, and plant species at exposure levels much below the safety limits. Exposure to RFR at 0.4 W/kg or more has been shown to cause DNA damage in at least 48 studies. Very sensitive plant and animal species to both natural and man-made EMF have been shown to have genotoxic consequences. The worldwide decline in insect populations is of particular concern. The biggest impacts of insects were seen at 1.2 GHz, the Larmor frequency. Superoxide production and the resonating of radical pairs are both connected to the Larmor frequency. This suggests that the effects of RFR vary with frequency. This spectrum covers both 5G and broadband speeds [88].

1.7. Effects of electromagnetic radiations on amphibians

Certain amphibian populations may be in decline due to deformities brought on by electromagnetic pollution (in the microwave and radiofrequency range). Studies on the impacts of this new sort of pollution are crucial, especially since amphibians are trusted bio-indicators. Further, several potential methods for assessing health risks must be presented in new studies.

2. Prospects

The literature on plant molecular and systemic responses to HF-EMF is expanding. Yet, the conditions of exposure are not consistent, demonstrating the diversity of approaches. As conditions in the near-field (i.e., close to the emission antenna) are unreliable and ill-defined, future research should focus on reducing exposure there. Communication devices (such as smartphones) should also be avoided as emission sources for the same reason; their built-in automation may make it difficult to accurately limit exposure levels. Although this phenomenon has been studied via numerical simulations, there is currently a lack of experimental proof supporting its presence in vivo and its formal contribution to the regulation of plant development. Light's effects on plants are due to a combination of interactions with chromophores and alternating electric fields formed in the medium that may interact with polar structures through dipole transitions. Further research is required to improve management and find solutions to the problems. The linked targets are likewise impacted by HF-EMF exposure. Thus, it is probable that HF-EMF uses similar mechanisms. Many plant responses to abiotic stress are known to be influenced by the pathways of interest, most notably Ca^{2+} metabolism.

3. Conclusion

There is general agreement among the studies done so far that plant stress is induced by radiofrequency electromagnetic fields exposure. Researchers have found that changes in biochemical (enzyme) and cellular (cell) activities occur in response to exposure and that these differences depend on the intensity and duration of the exposure. The plant's complete life cycle, from germination to fruiting, is likely to be affected by RF-EMF exposure. This raise concerns that mobile phone radiation could significantly alter the active component profile of medicinal plants and the quality of agricultural output. There have also been reports of less direct effects, such as on pollination and microbial interactions. There has been a call for more field research into the effects of mobile phone radiofrequency magnetic field on various plant species. To ensure that reasonably safe SAR values are maintained in places where agricultural food crops are grown on a big scale, it is necessary to establish safe SAR values for plants, particularly food crops. The same plant can be researched in a variety of environments. Thorough research can help to develop broad strategies for reducing and avoiding plant damage.

4. Conflict of interest

Authors declared no conflict of interest each other.

5. Acknowledgments

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6. Contributions

All the authors contributed equally in the current manuscript.

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