

Review

Enhancing sustainable plant production and food security: Understanding the mechanisms and impacts of electromagnetic fields

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ABSTRACT

The prevalence of electromagnetic fields (EMFs) caused by electromagnetic radiation is increasing in our daily lives, potentially bringing both adverse and beneficial effects. EMFs have garnered significant research attention in various disciplines, including agricultural science. However, our understanding of the impact of EMFs on the ecophysiological performance of plants under suboptimal conditions is limited. Despite this, there are indications that EMFs can improve crop productivity by enhancing seed germination, plant nutrition, precision farming, water use efficiency, root hydraulic conductance, plant water uptake, anti-oxidative defense, pest prevention, stress signaling, and hormonal pathways. This review highlights the practical application of EMFs for increasing plant biomass production by elucidating the underlying mechanisms involved in seed germination, plant growth, water relations, ion flux, photosynthesis, and antioxidant defense. We also highlight the prospects for using EMFs in sustainable agriculture and their potential to alleviate the conventional agricultural pressures related to food security issues.

1. Introduction

The world is facing significant challenges due to environmental extremes resulting from global climate change. Compounded by the increasing population and its growing demands for food, water, shelter, and energy, these issues have become more complex than before. The competition for vital resources among societies threatens human civilization (Diamond, 2005). Reliable and adequate food and energy supplies are crucial for economic growth and development (Poudyal et al., 2019). The world's population reached 7.8 billion in March 2020 and a substantial portion of agricultural land is now being used for biofuel feedstock production (Ajanovic et al. 2011; Maxwell, 2021). Consequently, finding solutions to address the competing food and energy production demands is crucial (Hasnain et al., 2023).

The availability of freshwater resources worldwide is estimated to be less than 3% of total water resources, with the majority being saltwater

stored in oceans and seas. Furthermore, only about 0.5% of the Earth's freshwater is available as surface water in lakes, rivers, and swamps while the remainder is inaccessible in the form of deep groundwater or icecaps and glaciers (Manju and Sagar, 2017). Efficient water management is critical for securing food production. Research focused on developing new approaches for water conservation in agriculture is of utmost importance (Askari et al., 2023; Hasnain et al., 2023; Abideen et al., 2020). Another challenge affecting food production is increasing soil salinization and drought frequency and intensity, particularly in arid and semi-arid regions. Using salt-affected soils for agriculture is challenging due to the adverse effects of high salt levels on plant growth and crop yield (Tuteja, 2007; Bano et al., 2022). Drought and salinity disrupt cellular metabolism, inhibit the activities of some enzymes, impede plant growth, and even lead to plant death (Zhang et al., 2019; Abideen et al., 2020; Munir et al., 2022). Salinity and water deficit can induce oxidative and osmotic stress, disrupting the functionality of plant

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cell lipids, protein, and DNA (Abideen et al., 2020; Nalina et al., 2021). Heavy rainfall and inadequate drainage contribute to flooding, overflowing rivers, and damage to different soil types, particularly on steep slopes (Shah et al., 2020). Flooding also directly affects plant growth and photosynthesis by altering the rate of oxygen diffusion in plant cells and mitochondrial respiration (Bhusal et al., 2020).

The global coronavirus (COVID-19) pandemic has further exacerbated the challenges associated with food security. The lockdown of billions of people inside their homes to curb the spread of the virus resulted in severe food security issues (Pulighe and Lupia 2020), particularly for countries that heavily rely on food imports, such as many countries in the Arab Gulf region. Border closures and movement restrictions increased food costs and limited food exports. Therefore, countries facing drought, limited water resources, and high temperatures need to explore new technologies to enhance food production under harsh climatic conditions and nutrient-poor soils. Addressing future food security challenges during global pandemics and rapid urban population growth requires identifying unconventional food sources and increasing crop productivity. The current rise in food prices due to market demands, economic currency devaluation, and inflation is causing a global crisis. Food insecurity is a significant threat worldwide, particularly in countries with high population growth rates and harsh climatic conditions, such as extreme temperatures and low precipitation, which limit crop production. The lack of available non-renewable natural resources, such as freshwater, and inadequate soil fertility for agriculture, are driving forces behind food insecurity. Climate change further exacerbates food insecurity by reducing the growing season duration. Therefore, the agricultural sector must adapt and incorporate safe technologies like electromagnetic fields (EMFs) to increase food production effectively. The mismanagement of food supply contributes to food shortage and waste risks.

Electromagnetic radiation, particularly in the form of sunlight, is essential for photosynthesis, the process by which plants convert sunlight into energy. Different wavelengths of light have specific effects on plant growth and development, with plants requiring red (600–700 nm) and blue (425–450 nm) light for optimal photosynthesis. Controlling the quality, intensity, and duration of light exposure using artificial lighting systems can enhance plant growth and increase crop yields in indoor and controlled environment agriculture, contributing to food security. Studies have shown that electromagnetic radiation influences the biological domain, including the agriculture sector. Electromagnetic radiation from various sources, such as power lines, wireless communication devices, and even sunlight, can affect plant growth, development, and overall agricultural productivity. Researchers are studying the specific effects of different types of radiation and exploring ways to mitigate potential negative impacts while harnessing the positive ones. Various wavelengths of electromagnetic radiation can trigger specific plant responses and growth patterns. For example, red light promotes stem elongation, while blue light stimulates leaf expansion. Specialized lighting systems enable farmers to optimize plant growth and increase agricultural productivity by controlling light wavelengths and intensities, even in indoor or low-light environments. Numerous research investigations have examined the effects of electromagnetic radiation and its significant impact on seed vigor, germination responses, plant growth, wastewater treatment for irrigation, photosynthesis, mineral nutrition, anti-nutrient, and pest prevention.

Research has shown that electromagnetic radiation can benefit seed germination (e.g., Ibrahim et al., 2020). Different wavelengths, intensities, and durations of electromagnetic radiation can trigger specific responses in plants, such as phototropism (growth toward light), photoperiodism (regulation of flowering time), and gravitropism (response to gravity). Electromagnetic radiation, specifically light, regulates plants' internal biological clocks, controlling various physiological processes such as stomatal opening and closing, nutrient uptake, and hormone production. A pre-sowing treatment for seeds with reduced dormancy using ultraviolet (UV) radiation increased salinity tolerance

compared to unprimed seeds (Ouhibi et al., 2014). In addition, exposure to electromagnetic radiation can benefit the seed germination cycle and nutrient uptake. However, plants can also experience stress from electromagnetic radiation when the intensity, frequency, or duration of exposure exceeds their optimal range or capacity. Stress is defined as any external factor that adversely affects normal plant functioning. When exposed to excessive electromagnetic radiation, plants may suffer negative impacts on growth, development, and overall agricultural productivity. Pollinators such as bees, butterflies, and birds are attracted to flowers primarily through visual cues, including color, shape, and patterns. Electromagnetic radiation in the visible light spectrum determines the colors perceived by these pollinators. Flowers have evolved specific color patterns to attract pollinators sensitive to certain light wavelengths. Bees, in particular, are attracted to ultraviolet (UV) light (e.g., Mori et al., 2023), which is invisible to humans but visible to bees. UV patterns on flowers guide bees to the nectar and pollen resources within the flowers, facilitating pollen transfer from male to female reproductive structures, resulting in fertilization and seed production. While moderate exposure to sunlight, including UV radiation, is essential for photosynthesis and plant health, excessive and prolonged exposure can lead to detrimental effects. Ultraviolet (UV) radiation, particularly UV-B (280–315 nm) and UV-C (100–280 nm), can cause DNA damage to plant cells. UV-B radiation primarily induces DNA lesions, such as pyrimidine dimers and DNA cross-links, disrupting normal DNA replication and transcription processes. UV radiation can also generate reactive oxygen species (ROS), highly reactive molecules that can cause oxidative damage to cellular components, including lipids, proteins, and DNA, leading to cellular dysfunction and skin cancer-like effects in plants. Excessive UV exposure can inhibit photosynthesis, reduce plant biomass, alter leaf morphology, and impair reproductive processes.

Microwave radiation (MWR) can affect the *Clitellate* (segmented worms belongs to annelids) population, which acts as a soil fertilizer and protective agent, impacting plant growth (e.g., Kim, 2019). While electromagnetic radiation, particularly light, is essential for plant growth as it serves as a food source for photosynthesis and influences growth, variations in exposure duration, wavelength, or intensity can act as plant stressors, affecting plant fitness and survival. In addition to electromagnetic radiation, various environmental factors such as drought, salinity, temperature variations, floods, pollination, and pathogen infestation can directly or indirectly stress plants, impacting their growth and production. However, low doses of electromagnetic radiation offer a novel approach to enhancing plant growth and production. It is important for farmers to carefully manage electromagnetic radiation exposure to optimize crop growth and minimize the adverse effects on plant health and agricultural productivity. Studies have shown that controlled and appropriate doses of electromagnetic radiation can benefit plant cultivation and crop production.

2. Electromagnetic radiation

Electromagnetic radiation consists of synchronized oscillations of electric and magnetic fields perpendicular to each other and the direction of energy and wave propagation. These propagate as electromagnetic waves. Electromagnetic radiation can be visible light, radio waves, microwaves, and X-rays. It can travel through space and can even penetrate solid objects. Electromagnetic radiation is also used in many applications, such as communication, medical diagnostics and therapies, and imaging (Rouhi et al., 2022). The characteristic parameters of these waves are frequency, wavelength, and energy. Frequency is the number of cycles per second, the wavelength is the distance (in meters) between two peaks of episodic signals, and energy is the amount of activation energy required to move negatron-charged particles over one-volt potential (measured in electron volts, eV). Wireless communication has recently become prevalent, replacing traditional wired-line transmission systems. Technologies such as 4 G/5 G cellular systems, global

Table 1
Electromagnetic wave spectrum.

EM waves	Frequency	Wavelength	Per photon energy
<i>Ionizing radiation</i>			
Gamma rays	30 EH-300 EH _z	10pm-1pm	124 k-1.24 MeV
Hard X-rays	3 E-30 EH _z	100 pm-10 pm	12.4 k-124 keV
Soft X-rays	300 P-3 EH _z	1 nm-100 pm	1.24 k-12.4 keV
	30 P-300 PH _z	10 nm-1 nm	124-1.24 keV
Extreme ultraviolet	3 P-30 PH _z	100 nm-10 nm	12.4-124 eV
<i>Visible light</i>			
Near ultraviolet, visible light	300 T-3 PH _z	1 μm-100 nm	1.24-12.4 eV
<i>Near-infrared</i>			
Mid-infrared	30 T-300 TH _z	10 μm-1 μm	124 m-1.24 eV
Far infrared	3 T-30 TH _z	100 μm-10 μm	12.4 m-124 meV
Microwave	300 G-3 TH _z	1 mm-100 μm	1.24 m-12.4 meV
Extremely high frequency	30 G-300 GHz	1 cm-1 mm	124 μ-1.24 meV
Super high frequency	3 G-30 GHz	1 dm-1 cm	12.4 μ-124 μeV
Ultra high frequency	300 M-3 GHz	1 m-1 dm	1.24 μ-12.4 μeV
<i>Radio wave</i>			
Very high frequency	30 M-300 MHz	10 m-1 m	124 n-1.24 μeV
High frequency	3-30 MHz	100 m-10 m	12.4 n-124 neV
Medium frequency	300 k-3 MHz	1 km-100 m	1.24 n-12.4 neV
Low frequency	30 k-300 kHz	10-1 km	124 p-1.24 neV
Very low frequency	3 k-30 kHz	10 ² -10 ¹ km	12.4 p-124 peV
Ultra low frequency	300-3 kHz	10 ³ -10 ² km	1.24 p-12.4 peV
Super low frequency	30-300 Hz	10 ⁴ -10 ³ km	124 f-1.24 peV
Extremely low frequency	3-30 Hz	10 ⁵ -10 ⁴ km	12.4 f-124 feV

positioning systems, Wi-Fi devices, WIMAX (Worldwide Interoperability for Microwave Access), LTE (long-term evolution), RFID (Radio Frequency Identification), and IoTs (Internet of Things) have revolutionized communication worldwide. Devices such as Wi-Fi modems, routers, switches, microwave links, and satellite transponders emit EMFs as they receive and transmit information using radio frequencies (Tachibana, 2022). In addition, the base transceiver stations for cellular communication contribute to the electromagnetic radiation in our environment. Our lives have become highly dependent on these technologies, and it is challenging to imagine living without them.

Consequently, all living organisms are exposed to natural and artificial electromagnetic radiation sources. Natural sources include radiation from the sun, stars, Earth's terrain, and radionuclides, while human-made/unnatural sources include radio frequency (RF), microwave (MW), L-band satellites, and S & C-band radar frequencies used for communication purposes. These various forms of radiation affect living creatures in terms of specific absorption rate, which refers to the amount of incident electromagnetic radiation absorbed over a wide frequency spectrum.

2.1. Types of electromagnetic field radiation

Electromagnetic radiation encompasses various frequencies and wavelengths, forming the electromagnetic spectrum (Table 1). This spectrum begins with longer wavelengths of non-ionized low-energy radiation, such as radio waves and microwaves, progresses through infrared and visible light, and extends to shorter wavelengths of higher-energy radiation, such as ultraviolet, X-rays, and gamma rays. Microwaves are used primarily for high-bandwidth communication systems, while radio waves are used for cellular communications (Table 1). High-frequency electromagnetic fields (HF-EMFs) are human-made non-ionizing radiations that do not occur naturally, except for low amplitude, very high-frequency cosmic radiation. HF-EMFs have frequencies ranging from 300 MHz to 3 GHz and wavelengths ranging from 1 m to 10 cm. These fields are used in wireless technology applications, such as cell phones and Wi-Fi-connected devices (Balmori, 2009). The widespread use of wireless telecommunication has electromagnetic pollution in urban and rural areas (Galeev, 2000).

2.2. Impact of electromagnetic field radiation on plants

Numerous studies have assessed the impact of HF-EMF on plants with varied results (Reddy et al., 1998; Kiong et al., 2008; Paparella et al., 2015; Yan, 2015; Jiao et al., 2016; Ibrahim et al., 2020). While our understanding of electromagnetic radiation's effects on plants is growing, the overall picture remains unclear. In this section, we have thoroughly reviewed studies that have assessed the impacts of HF-EMFs on seed germination (the most critical stage in plant life) and plant growth, considering different molecular, cellular, and physiological effects on plants (Fig. 2).

2.3. Impact of electromagnetic field radiation on seed germination

Agricultural sustainability involves developing technologies and practices that enhance food productivity without adversely affecting environmental goods and services (Pretty et al., 2006; Araujo et al., 2016; Rifna et al., 2019). Seeds are the primary independent structures responsible for the next generation of plants, maintaining genetic material and improving species diversity and production capacity (Shariffar et al., 2015). Seed germination is a critical stage in plant growth, influenced by intrinsic and extrinsic factors (Bewley and Black, 1994). Under favorable conditions, seed germination and seedling establishment occur quickly. However, under extreme conditions, seeds exhibit an intrinsic blockage of germination known as dormancy, enabling them to overcome unfavorable periods for seedling establishment (Bewley et al., 2006; Rifna et al., 2019). Thus, high-vigor seeds are essential for crop establishment and sustainable productivity. Fast seed germination is needed for improved seedling emergence and plant growth, leading to increased productivity. Various chemical and physical methods can enhance seed germination under unfavorable conditions (Baskin and Baskin, 1998; Bewley et al., 2006), with common practices involving fertilizer or pesticide applications (Ramteke et al., 2013; Rifna et al., 2019). However, while fertilizer applications can significantly increase yields, they can also adversely affect the environment and living organisms. Physical pretreatments/methods/factors, such as exposure to electromagnetic radiations like ultrasound waves and ionizing radiation, are promising alternatives for increasing agricultural production yields and improving pathogen crop protection during plant growth and long-term storage (Araujo et al., 2016; Rifna et al., 2019). Physical methods of seed stimulation offer several advantages over conventional chemical-based treatments, including reducing fertilizer use and seed disinfection during storage and before sowing.

Recent research has focused on the effects of electromagnetic waves (EW), magnetic field (MF), ultrasound (US), and ionizing radiation (IR) treatments on seed vigor, germination responses, and seedling growth (Ibrahim et al., 2020). The effects of different electromagnetic wavelengths, such as laser, infrared, and polarized light, have been assessed for seed germination (Ibrahim et al., 2020). Halgamuge (2017) reported that 169 experimental observations were published in 45 peer-reviewed journals from 1996 to 2016, discussing the potential effects of electromagnetic radiation on plants. Table 2 presents similar studies conducted in more recent five years (2016–2020). Tolomei (1893) was the first to report that electromagnetic radiation could accelerate seed germination. Microwave electromagnetic radiation increases seed germination by reducing or changing main chemical reactions (Reddy et al., 1998). In addition, microwave electromagnetic radiation stimulates the formation of hydrogen (H^+) and hydroxyl (OH^-) ions in seeds which is important for the oxidative stress cycle in seed. In addition, glucose production induced by electromagnetic radiation promotes seed germination and activates enzyme systems, improving seedling growth and plant productivity (Ma et al., 2020).

The impact of electromagnetic radiation depends on species, seed moisture content, seed size (fresh weight and seed area), environmental factors during seed imbibition, such as temperature, light duration, and humidity, and the exposure, duration, and intensity of electromagnetic

Table 2
Effect of electromagnetic waves on seed germination in different species.

Types of EM wave	Species	Duration of exposure	Frequency Hz	Effects	Refs.
Magnetic field	Wheat	5, 10, 15 min	5, 10, 15 mT	Increased germination rate	Hussain et al., 2020
Magnetic field	<i>Raphanus sativus</i>	3, 12 min	6, 8, 20 mT at 50 Hz	Increased germination rate and vigor index	Konefal-Janocha et al. 2019
Magnetic field	Soybean	Up to 20 days	1500 nT at 10 Hz for 5 h per day	Increased seed germination by modulating enzyme activities	Radhakrishnan 2019
Magnetic field	<i>Zea mays</i> L.	1, 3, 5, 7 min	50, 250 mT	Increased mean germination time, germination speed, and germination rate at 50 mT	Torres et al. 2019
Magnetic field	<i>Amaranth</i>	30 s	50 Hz	Improved seed germination	Kornarzyński et al., 2018
Magnetic field	<i>Catharanthus roseus</i>	10, 20, 30 min	50, 100, 150 mT	Improved seed germination under saline conditions; highest germination (74.4% and 73.0%) after 20 and 30 min exposure to 100 mT	Zaredost et al., 2014
UV-C radiation	Barley	30, 60, 120 min	254 nm	Seed exposure for 120 min increased seed germination (88.3%)	Lazim and Ramadhan 2020
UV-C radiation	<i>Sorghum bicolor</i> L. Moench	0, 30, 60 min	250 nm	Positive or negative effect on selected germination parameters, depending on exposure time	Lazim and Nasur 2017
Microwave radiation	<i>Vigna radiata</i> L., <i>Phaseolus vulgaris</i> L.	5, 15, 30 s		Improved germination% and rate	Ibrahim et al., 2020
Microwave radiation	Green gram	10, 30, 60 s		Seed exposure for 30 s increased seed germination	Dave et al. 2020
Microwave radiation	Barley	5, 10, 20 s	2450 MHz	Seed exposure for 10 s increased seed germination (93.33%)	Lazim and Ramadhan 2020
Microwave irradiation (MR)	<i>Brassica napus</i> L.	0, 30, 60, 90 s	2.45, 5.70, 9.30 GHz	Highest seed germination at 2.45 GHz for 30 s	Farid et al., 2017
Microwave radiation	<i>Zea mays</i>	0, 30, 60, 90, 120 s	100, 200, 300 Ws	200 W at 90 s significantly increased germination and seedling growth	Danesh et al., 2017
Gamma radiations	<i>Cucumis sativus</i> , <i>Abelmoschus esculentus</i>	600 Gy h ⁻¹	0, 50, 100, 150, 200 Gy	Increased seed germination (100%) compared to untreated seeds (20%)	Jaipo et al., 2019
Gamma radiation	<i>Vigna unguiculata</i> [L.] Walp.	3 d	0, 100, 200, 300, 400, 500 Gy	Improved seed germination and vigor at low doses	Olasupo et al., 2016
Gamma radiation	<i>Lathyrus chrysanthus</i>	0.8 k Gy h ⁻¹	0, 50, 100, 150, 200, 250 Gy	Increased germination and improved seedling growth	Beyaz et al. 2016
Ultrasonic waves	<i>Thymus vulgaris</i> L.	4, 8, 12 min	20, 40, 60 KHz	Improved seed germination and vigor indices	Nader et al., 2019
Ultrasound waves	Rice	5 min	25 kHz (16 W/L)	Reduced energy use during germination and improved sprouting speed	Ding et al., 2018
He-Ne laser	<i>Amaranth</i>	10 s	3 mW.cm ⁻²	Improved seed germination	Kornarzyński et al., 2018
He-Ne laser	<i>Scorzonera hispanica</i> L.	0, 1, 5, 10, 30 min	632.8 nm	Germination increased after 1 and 5 min exposure	Dziwulska-Hunek et al., 2016
Radiofrequency (EMF)	<i>Helianthus annuus</i>	5, 10, 15 min	5.28 MHz	15 min treatments increased germination rate by 24%	Mildaženė et al., 2019
Radiofrequency	Tomato	4–5 h	9.3 GHz	Increased β–1,3-glucanase activity stimulated the germination rate and seedling vigor	Kumari et al., 2018
Radiofrequency	Wheat and corn	10 min	27 MHz	Increased germination rate in wheat	Jiao et al., 2016
Radiofrequency	<i>Rhododendron smirnowii</i> Trautv., <i>Morus nigra</i> L.	5, 10, 15 min	5.28 MHz	Stimulated germination of freshly harvested <i>R. smirnowii</i> seeds (by up to 70%), but reduced germination of fresh <i>M. nigra</i> seeds (by 24%)	Mildaženė et al., 2016
Electromagnetic field	<i>Thymus vulgaris</i> L.	5, 15, 30 min	5, 50, 100 mT	Improved all germination traits and indices	Nader et al., 2019
Low-power electromagnetic field	<i>Setaria italica</i> (Foxtail millet)	30 min	10 Hz	Improved seed germination and other characteristics	Ramesh et al., 2020
Pulsed electromagnetic field (PEMF)	Soybean	0, 30, 60, 90 min	16, 24, 30, 72 Hz	Increased seed germination by up to 8% and yield by 960.5 kg, or 21%, in the field	Dukic et al. 2017
Electromagnetic field	<i>Sorghum bicolor</i> L. Moench	0, 3, 6, 9 h	125 mT	Highest seed germination after 6 h by 40.50%	Lazim and Nasur 2017
Electromagnetic field	Durum wheat	0, 15, 30, 45 min	15, 30, 45 MF	Enhanced germination, tillering, dry weight, leaf area, chlorophyll content, photosynthetic rate, and yield	Katsenios et al., 2016
Electrical field	<i>Cicer arietinum</i> L.	24 h	1.5 V	Higher germination with physiological changes such as the formation of reducing sugars and increased protein content	Unsugmi et al., 2017
Electromagnetic radiation	Brown rice	6, 12 h	60, 70 GHz	Increased germination rate from 80% to 91.5–94.8%	Seo et al., 2016
Stationary magnetic field (SMF)	<i>Zea mays</i> L.	60, 120 min	100, 200 mT	Improved germination-related parameters	Shine et al., 2017

radiation. Reddy et al. (1998) demonstrated that microwave energy (2.45 GHz) significantly reduced seed-borne pathogens in wheat seeds without affecting seed quality. Besides, Rajagopal (2009) reported that microwave radiation increased seed viability and seedling growth in wheat, barley, and rye. Exposing barley seeds to MWR and UV-C radiation for 10 s improved seed germination (Lazim and Ramadhan, 2020). MWR effectiveness in germination depends on the seed's chemical profile, optimal germination temperature, and radiation exposure period (Jiao et al., 2016). Further, radio-frequency thermal treatments significantly affected the physiological properties of wheat and corn

seeds (Jiao et al., 2016), with a mild intensity treatment (65 °C for 10 min) increased seed vigor, germination frequency, and enzyme activities, including superoxide dismutase, catalase (CAT), and peroxidase (POD) (Jiao et al., 2016). Talei et al. (2013) concluded that microwave-radiated energy (2.45 GHz for 10 h) accelerated water molecules, increasing water absorption in undeveloped rice seeds. This led to increased germination and root and shoot lengths. Kumari et al. (2018) reported that MWR improved the germination and growth of tomato seedlings by upregulating enzyme activities.

2.4. Impact of electromagnetic field radiation on seed priming

Seed priming is a biotechnological tool for enhancing seed germination, plant establishment, and stress tolerance. Priming, also called sensitization or surfacing, is a simple, practical, effective, eco-friendly, and cost-effective approach to improving plant tolerance to various environmental stresses. It involves controlled seed hydration, enabling the onset of metabolic events before germination without protrusion from the root (Tanou et al., 2012; Hussain et al., 2016; Farooq et al., 2019; Mirmazloum et al., 2020). Seed priming can improve seedling emergence and stand establishment, induce early flowering, reduce seed dormancy, enhance nutrient uptake, and improve crop yield (Harris et al., 2007; Rehman et al., 2011; Singh et al., 2015; Ullah et al., 2019). Seed priming can also mitigate the adverse effects of various abiotic (salinity, drought, flooding, high temperature, high irradiance) and biotic (phytopathogens) stresses (Kausar and Ashraf, 2003; Basra et al., 2005; Guan et al., 2009; Sharma et al., 2014; Kumar et al., 2016). Increasing seed quality, germination, and seed formation through seed priming are important to increase crop yield (McDonald, 2000). Seed priming is also beneficial for recovering and reversing seed vigor after long-term storage (Zhao et al., 2018). Seed priming techniques include hydro-priming, biological priming, hormonal priming, redox priming, and solid-matrix priming. Their efficacy varies with species and type of stress (Ashraf and Foolad, 2007; Jisha et al., 2013; Farooq et al., 2019; Mirmazloum et al., 2020). While chemical priming is popular, a growing body of evidence shows that physical seed priming, including UV, X-rays, γ -irradiation, electromagnetic waves, and ultrasound, are used for seed priming (Yan, 2015; Wojtyla et al., 2016; Mahmoudi et al., 2019).

In the last few years, electromagnetic radiation has developed into an innovative method of priming seeds (Fig. 3), with ionizing and microwave treatments proving to be the most effective (Paparella et al., 2015; Panuccio et al., 2018). Typically, UV solar radiation is classified by wavelength. UV-C radiation (100–280 nm) is trapped by the ozone layer and absorbed by other layers that trap greenhouse gasses. The ozone layer partly filters UV-B radiation (280–315 nm) but does not absorb UV-A radiation (315–400 nm). Ouhibi et al. (2014) reported that lettuce seeds primed with UV-C radiation exhibited more salinity tolerance than unprimed seeds due to improved seed germination and seedling vigor (Rozbeh et al., 2011). UV-A and UV-C radiation improved seed quality and induced early sprouting in various crop plants (Dhanya and Puthur, 2017; Sadeghianfar et al., 2019). UV-A exposure to mung beans increased seedling emergence, leaf area, plant length, and dry biomass, with 6 h of UV-A radiation seed priming resulting in 100% germination (Hamid and Jawaidd, 2011). Compared with the visible portion of the spectrum, UV light increased seed vigor and accelerated seedling emergence in winter wheat 'Moskovskaya 39' and naked oats 'Vyatsky' (Kondrateva et al., 2020). Short-term seed priming with low-dose gamma radiation accelerated germination and enhanced seedling establishment in various wheat varieties (Sen and Puthur, 2020). Low-dose exposure to gamma radiation accelerated the germination cycle and enhanced seedling growth in lettuce and barley (Marcu et al., 2013; Volkova et al., 2019). Some studies have shown that short-term seed exposure to microwaves increased germination rates, but long-term exposure had adverse effects (Ragha et al., 2011; Lazim and Ramadhan, 2020; Brust et al., 2021). Similarly, Sahin (2014) reported that prolonged microwave exposure decreased the seed germination rate in plants, indirectly reducing their productivity.

2.5. Impact of electromagnetic field radiation on plant growth and biochemical and physiological responses

Non-ionized electromagnetic radiation affects humans, animals, and plants and responds to everything connected to the internet through non-ionized EMFs. Mobile phone receivers, base transceiver station towers, and wireless routers have increased amounts of non-ionized

electromagnetic radiation, which directly affects plant biochemical and physiological processes, including plant anatomical features, mineral acquisition, water balance, chlorophyll, and photosynthesis (Fig. 4). Electromagnetic-radiated frequencies for MWR at bands corresponding with wireless routers and mobile devices affected leaf anatomical features in *Petroselinum crispum*, *Apium graveolens*, and *Anethum graveolens*, including reduced cell wall thickness and size of chloroplasts and mitochondria (Soran et al., 2014; Kaur et al., 2021).

The perception and response of plants to EMF of various frequencies have been studied in several studies. Protein conformation, membrane potential, and ligand/receptor binding capacity may be responsible for these responses (Kaur et al., 2021). Several biological processes are activated in plants when exposed to EMF, including ROS production, scavenging metabolism, and calcium metabolism (Vian et al., 2016). Besides, mobile device radiation enhances the emissions of essential oil contents in plant seeds, while wireless routers inhibit this effect (Soran et al., 2014). Inoculating soil with Annelida (ringed worms) enhanced plant growth, antioxidant defense activities, and nutrient acquisition, increasing leaf and flower numbers, cell area, and chlorophyll content (Kaur et al., 2017). MWR affected vermicast potency for plant growth and antioxidant activities in Chinese cabbage seedlings (Abbey et al., 2017). Two major cellular processes, calcium movement, and ROS generation, are disturbed by EMF exposure. A signal such as EMF induces a spatially and temporally varying Ca^{2+} signature, which is then translated into cellular responses through proteins (Kaur et al., 2021). Calcium chelators or calcium channel blockers prevented the accumulation of stress-related transcripts that normally arise after exposing tomato plants to EMF. This suggests that Ca^{2+} might be an earlier sensor for detecting the plant response to EMF exposure (Pall, 2016).

Electromagnetic MWR decreased seedling growth but promoted the growth of older plants (*Spirodela polyrhiza*) by an average of 150% compared with unexposed plants (Magone 1996). EMF has inconsistent effects on enzyme activity. While the hydrolytic enzymatic activities (α - and β -amylases and invertases) responsible for the production of soluble sugar increased in germinating seeds after exposure to HF-EMF (Kumar et al., 2015; Sharma et al., 2009), the starch phosphorylase activity—phosphorolytic and potentially reversible—was diminished. In contrast, HF-EMF exposure (900 MHz) decreased soluble sugars related to the Krebs cycle and pentose phosphate pathway in *Plectranthus* (Lamiaceae) leaves (Kouzmanova et al., 2009), suggesting that seeds and adult leaves respond differently to HF-EMF exposure. In addition, weak magnetic fields (75 Hz; 1.5 mT) increased C/N and C/P ratios, indicating the production of more recalcitrant litter that is slower to decompose, indicating that weak MF treatments may help enhance soil C storage and reduce CO_2 emissions (Balino et al., 2023). Ultrasonic treatment may increase protein solubility by breaking weaker hydrogen bonds, resulting in conformational changes and reduced size of protein particle aggregates, eventually increasing protein–water interactions (Arzeni et al., 2012; Berra et al., 2021).

2.6. Impact of electromagnetic field radiation on plant water recycling

Electromagnetic field radiation is used in plant water recycling processes, particularly to treat wastewater and drinking water, eliminating pathogens, heavy metals, and other pollutants in sewage sludge and wastewater. Effective water recycling approaches have become crucial to increasing water scarcity and pollution concerns. Irradiation technologies like gamma, ultraviolet, ultrasound, and X-ray are used for wastewater treatment for decontamination purposes. Ultraviolet irradiation, for example, is an alternative to chlorination in wastewater treatment plants.

As the global population grows, more regions are expected to face water scarcity issues. By 2050, more than 44% of the world's population is estimated to live in water-scarce regions (Scheierling et al., 2011). As a result, wastewater treatment has gained attention to increase the available water supply. Besides, UV radiation has been used in soil

solarization, a cost-effective disinfection technology that uses UV radiation to kill harmful microorganisms and weed seeds (Boyle et al., 2008; Gomez-Couso et al. 2009; Sichel et al., 2009). Solar solarization is required for food security (UNDP, 2006). Besides, MWR has also been used to pretreat/normalize wastewater sludge (Wojciechowska 2005; Kennedy et al., 2007). Moreover, some studies have shown that MWR can effectively decontaminate soil, sludge, and wastewater, making it an innovative and promising thermal source technology for treatment purposes (Nuchter et al., 2004; Wu, 2008).

2.7. Impact of electromagnetic field radiation on plant photosynthesis

Photosynthesis is the most crucial component of the biosphere for primary production (Taiz and Zieger 2010). It is a complex process driven by a series of photochemical and chemical reactions in which electromagnetic energy is converted to chemical energy for biosynthesis (Taiz and Zieger, 2010). In photosynthetic organisms, both the quantity (duration and intensity) and quality (color or wavelength) of electromagnetic waves are vital for regulating growth and various physiological processes (Senavirathna et al., 2014; Tang et al., 2017). However, most studies on the effects of electromagnetic radiation on photosynthesis have focused on the phenotypic level, with scarce information on the mechanism of electromagnetic waves in photosynthesis. How does electromagnetic radiation or photo-electromagnetic coupling affect photosynthesis, and does electromagnetic radiation and light have homologous receptor/s?

Plant growth and yield mainly depend on efficient photosynthesis (Taiz and Zieger, 2010). Chlorophyll, involved in all primary aspects of photosynthesis, comprises a small group of compounds with closely related structures recognized as indispensable photoreceptors in plants and bacterial photosynthesis (Taiz and Zieger, 2010). Sandu et al. (2005) reported that frequent, prolonged exposure to ultra-high frequency EMFs resulted in chlorophyll degradation in black locusts. Typically, chlorophyll *b* is more sensitive to the EMF than chlorophyll *a* (Taiz and Zieger, 2010). Ultrastructural observations of irradiated plant cells with gamma radiation revealed significant structural changes in chloroplasts (Teramura and Ziska, 1996; Kiong et al., 2008; Borzouei et al., 2010). For example, wheat seedlings exposed to low-intensity gamma radiation had increased chlorophyll contents, especially chlorophyll *a*, but exposure to higher intensities was severely damaging, particularly for chlorophyll *b* (Borzouei et al., 2010). Kiong et al. (2008) reported that reductions in chlorophyll *b* are related to more selective destruction of its biosynthesis or its precursors' degradation. However, improved chlorophyll content in red pepper plants irradiated with low gamma radiation intensities was associated with photosynthesis modulation resulting in stimulated growth (Kim et al., 2004). Electromagnetic radiation exposure significantly reduced chlorophyll *a* and *b* contents but increased carotenoid content and non-enzymatic antioxidant activity in irradiated plants of *Satureja bachtiarica* (Vishki et al., 2012).

The intensity, exposure time, and radiation wavelength of electromagnetic radiation directly affect leaf anatomy (Teramura and Ziska, 1996; Tang et al., 2017). For example, exposure to UV-B radiation increased the number of spongy tissues in *Brassica carinata* and *Medicago sativa* leaves while increasing palisade tissues in *B. campestris* (Bornman and Vogelmann, 1991). More prolonged exposure to electromagnetic radiation affected stomatal conductance and increased the evaporation rate in *Fraxinus excelsior*, *Betula pendula* and *Tilia cordata* plants disturbing plant metabolism (Teramura and Ziska, 1996; Vishki et al., 2012). UV-B radiation induced stomatal closure in beans, soybean, and cucumber (Teramura et al., 1980; Bennett, 1981). Plant exposure to wireless devices operating microwave radiation (MWR, 2.45 GHz) decreased the green pigment in leaves. Moreover, MWR negatively affected photosynthesis by reducing stomatal conductance (Terashima et al., 2006). UV radiation, especially UV-B (280–320 nm) in solar light, affects many photosynthetic processes, including oxygen evolution, pigment synthesis, CO₂ fixation, and electron flow transport in PSII

(Sicora et al., 2003; Wang et al., 2011; Rastogi et al., 2014; Mohajer et al., 2015; Sompornpailin and Kanthang, 2015).

The penetration and internal distribution of UV-B radiation vary among plant species and depend on epidermal thickness, leaf anatomy, pigments, and other physiological changes that result from UV-B exposure. Day (1992) reported that, among 22 plant species, the leaves of herbaceous dicots had the deepest UV-B rays, woody monocots and grasses had intermediate penetration, and conifer needles had almost no penetration. UV-B irradiation affects light harvesting and the photochemical apparatus by causing ultrastructural damage to chloroplasts (Allen and Young, 1978), altering the exciton transfer between antenna pigments of different reaction centers (Renger et al., 1986), and changing photosynthetic pigments, especially chlorophyll (Vu et al., 1982; Deckmyn et al., 1994). In addition, the breakdown of the D1 protein in the PSII reaction center may explain the reduced efficiency of light-harvesting reactions in UV-irradiated plants (Pazuki et al., 2017). Therefore, reducing photosynthetic capacity is essential in plant carbon dynamics under high UV-B effects (Pazuki et al., 2017; Tang et al., 2017). Plant leaf anatomy is directly affected by electromagnetic radiation, including strength, exposure time limit, and radiation wavelength, affecting plant production and photosynthesis (Teramura and Ziska, 1996; Tang et al., 2017). Prolonged exposure to electromagnetic radiation affects stomatal conductance and increases the evaporation rate, disturbing plant metabolism (Kaur et al., 2021). Exposure to wireless devices operating MWR (2.45 GHz) decreased plant leaf green pigment but did not affect green chlorophyll pigment or cell structure.

2.8. Impact of electromagnetic field radiation on plant mineral nutrition

Mineral nutrition significantly affects plant survival, especially in contaminated environments. For example, mineral accumulation in acidic soils can alleviate heavy metal toxicity (Wang et al., 2020). Schmutz et al. (1996) reported a negative correlation between Ca and S concentrations in beech leaves and microwave exposure (2.45 GHz) with spectral flux densities of 100–300 W m⁻². In another study, exposure of soybean to UV-B radiation increased N and P contents by 9 and 16%, respectively, but decreased Mg and Ca contents by 9 and 24% (Shen et al., 2009); the authors suggested that reallocation of nutrients such as P, K, and Ca to roots under UV-B radiation, in combination with silicon, enhanced soybean stress tolerance.

Earthworms and decomposed materials improve soil macronutrients and micronutrients, and plant productivity (Chattopadhyay, 2014). Microwaving soil for 2, 2.5, 3, 4, or 6 min increased the number of amino acids, carbohydrates, and manganese in soil components, with no significant effect on P, K, Ca, Zn, Mg, or N (Ferriss, 1984). Oscillating MF exposure to soil increased Strawberry and Camarosa plants N, K, Ca, Mg, Cu, Fe, Mn, Na and Zn contents but decreased P and S contents (Esitken and Turan, 2004). These findings indicate that certain soil microorganisms survive MWR and contribute to releasing and metabolizing nutrients from dead cells during the regulated heating cycle (Hendricks et al., 1988).

2.9. Impact of electromagnetic field radiation on plant anti-nutrition and oxidative stress

Various methods, such as sterilization, antiseptics, pasteurization, and fumigation, can remove harmful plant pathogens from the soil. (MWR) is inexpensive for sterilizing soil, reducing soil-borne colonization, and preventing anti-nutrient pathogen growth (Ferriss, 1984; Tkalec et al., 2013). Bacteria are more heat tolerant than fungi, indicating they are more resistant to MWR (Tkalec et al., 2013). EMF affects Oxidative stress and directly concerns the irregularity between chemical and biological systems. A biological system under stress produces oxidative radicals, adversely affecting all system elements, including proteins, lipids, and DNA, and stimulates ROS with solid immunity against pathogens. The cellular signal transponder system is disturbed

by oxidative stress. Tkalec et al. (2007) showed that 900 MHz of electromagnetic non-ionizing radiation stimulated oxidative stress levels, but the outcome depended on radiation power level, treatment period, and modulation type. Tkalec et al. (2013) reported that 900 MHz of electromagnetic radio-frequency radiation with AM field modulation for 120 min increased DNA, damage protein, carbonyl substances, and lipids (peroxidation) compared to normal conditions. Antioxidant enzyme activities are also enhanced by electromagnetic radiation exposure; higher electrical field strengths (23, 41, 120 V m⁻¹). For example, exposure of *Allium cepa* roots to 2100 MHz of electromagnetic radiation enhanced malondialdehyde content and ROS production and altered antioxidant enzyme activities (Chandel et al., 2017).

Plant tissue culture is a highly flexible technology that contributes to the micro-propagation of thousands of transplants from a small portion of the parent plant. With the increasing global population, plant tissue culture has become essential for agriculture, horticulture, medical usage, and vegetative propagation. In plants, specific radiation doses alter explant morphology during in vitro propagation. This is a crucial factor in successful plant regeneration. Ultraviolet radiation has been found to affect explants, positively promoting cell division and enlargement. However, excessive exposure can be damaging, resulting in cell death (Katerova et al., 2012; Nazir et al., 2020). Besides, Broertjes and Van Harten (1978) reported that radiation affects the floral structures and colors of *Saintpaulia*, *Streptocarpus*, *Kalanchoe*, and *Achimenes* during in vitro propagation. Gamma radiation exposure in tissue culture systems can cause plant organs and callus tissue mutations (Anhufi et al., 2023). Higher doses of gamma rays can disrupt various physiological processes in plants, including protein synthesis, hormone stability, foliar gas exchange, water transport, and enzymatic activities (Esfandiari et al., 2008).

Light-emitting diodes (LEDs) are semiconductors that radiate light as currents flow through them. LEDs are widely used as a source of artificial light in plant tissue culture and growth systems. LED light, particularly blue light (440–490 nm), can promote the growth of plant tissue and seedlings. For example, chlorophyll contents increased in cultured rice plantlets under blue LED (Li et al., 2013).

2.10. Impact of electromagnetic field radiation on pest prevention

A significant concern in the agricultural sector is the prevalence of pathogens and pests and the affordability of organic fertilizers and pesticides. Farmers invest enormous amounts in weed and pest control. Electromagnetic exposure, particularly electromagnetic radiation, is an alternative solution for expensive pest chemical requirements. Electromagnetic RF and MW radiation disinfection are innovative methods that can control the survival or activity of pathogens and insect pests. These treatments offer rapid, pesticide-free, and cost-effective solutions compared to traditional pest prevention methods such as fumigation, insecticides, and herbicides. Weeds, in particular, pose a significant risk to crop sustainability, causing substantial crop losses worldwide (Oerke, 2006). Conventional weed control approaches involve pesticides and chemical fumigants that can adversely affect human health and the ecosystem. Electromagnetic radiation, initially introduced by Burdette et al. in 1929, offers a viable pesticide-free alternative for weed control.

Short-term exposure to UV-B radiation can deactivate the spread of fungi due to genetic and morphological changes that reduce the feasibility of propagation (Braga et al., 2001) and reduce the damage intensity of pathogens (Morandi et al. 2008; Costa et al., 2012). However, Macana and Baik (2018) reported that the concentration of UV-B radiation is a significant constraint for controlling disinfection potency. Full or partial captivation of solar UV radiation disrupts the growth cycle of several pathogenic fungi and modifies the sensory tendencies of many pests (Raviv and Antignus 2004). UV radiation may tamper with the activated host resistance to plant pathogens and destabilize the formation of pathogens and biological control agents (Ghini et al., 2012). High ultraviolet (UV-B) radiation increased the N content in plant cells, which

was linked to pest phytophagous prevention (Hatcher and Paul 1994). UV rays are generally effective for controlling weeds but are associated with practical issues such as fire hazards, potential health risks, and mutation chances.

The effect of UV radiation exposure depends on the species' developmental phase. Several experiments have shown that electromagnetic radiation can be used to monitor pests by disturbing their populations (Odemer and Odemer, 2019; Balmori et al., 2020). For example, RF exposure affected the weight, lifespan, and growth rate of tobacco hornworms as they proceeded through the larval stages (Schwartz et al., 1985). Electromagnetic MW radiation has shown potential for managing crop pathogen species, although its use in the farm environment may be limited due to high energy utilization and power requirements (Knezevic and Fennimore 2017). Microwave exposure effectively reduced pathogen pressures on wheat seeds and preserved crop quality and strength (Knox et al., 2013; Charoux et al., 2021). Ionizing gamma radiation is another method for disinfecting agricultural products and reducing pathogen transmission (Melki and Salami, 2008).

2.11. Impact of electromagnetic field radiation on plant biotic factors

Biotic pathogens, such as bacteria, fungi, viruses, nematodes, insects, and weeds, can affect plant health, such as growth rate, yield, quality, or resistance to other stresses. They interact with electromagnetic radiation in various ways, depending on radiation, pathogen, and plant types. RF radiation can modulate plant responses to biotic pathogens. For example, it enhanced the resistance of tomato plants to bacterial wilt caused by *Ralstonia solanacearum* but increased the susceptibility of wheat plants to powdery mildew caused by *Blumeria graminis* (Choi et al., 2020; Tanner et al., 2022). On the other hand, UV-B radiation induces the production of phenolic compounds that act as antioxidants or defense molecules against pathogens. It can also activate the expression of pathogenesis-related genes and induce systemic acquired resistance in plants. However, UV-B radiation can also impair the plant immune system by affecting the perception or signaling of salicylic acid or jasmonic acid (Zhong et al., 2021). Gamma rays induced resistance to fungal diseases in rice and wheat by activating defense-related genes or enzymes. They also induced resistance to viral diseases in tobacco and potato by interfering with viral replication or movement (Gallé et al., 2021). Red light can positively affect plant immunity by modulating the expression of defense-related genes, producing defense-related metabolites, and activating defense-related signaling pathways. It can be used to improve plant health and crop protection. Electromagnetic field radiation may influence insect behavior, pollination, herbivory, and plant-insect interactions. UV radiation, particularly the UV-C range (100–280 nm), has been investigated for its weed control potential. It can damage DNA and the cellular structures of plants, inhibiting weed seed germination and reducing weed growth. However, caution should be exercised as UV-C radiation can also adversely affect non-target organisms (Bajwa et al., 2015; Naruhn et al., 2021). Infrared radiation has been explored for weed control, specifically in the IR-A and IR-B ranges. It can generate heat and affect the thermal balance of plants, leading to desiccation and damage. IR radiation has shown potential for selectively controlling weeds without harming crops, and thermal-based weed control systems using IR radiation have been developed and tested (Santos et al., 2020). Specific RF ranges, such as 0.1–10 MHz, have demonstrated promising results in inhibiting weed germination and growth. However, the impact of UV-B radiation on biota is a significant concern (Sharma et al., 2017), as an increase in solar UV-B radiation caused by human activities can result in the loss of the stratospheric ozone (O₃) layer, impacting terrestrial ecosystems, including plant life.

2.12. Impact of electromagnetic field radiation on plant abiotic factors

Plants can adapt to environmental changes, including EMF radiation (Olsen and Dineva, 2017). Increased temperatures, influenced by solar

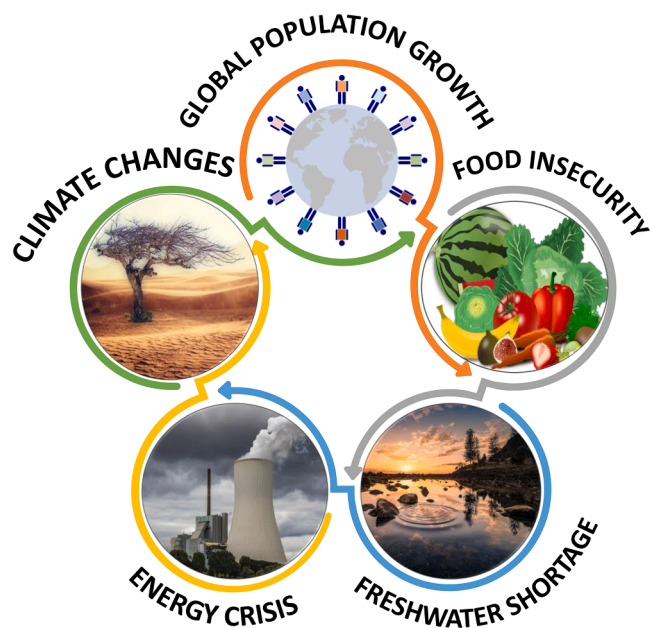


Fig. 1. Global issues that affect sustainable agricultural development.

radiation, directly and indirectly affect plant growth and development. Direct effects include changes in physiological processes such as photosynthesis, respiration, and transpiration. Higher temperatures can enhance photosynthesis rates initially, but if they exceed the optimal range for a specific plant species, photosynthetic efficiency can decline, decreasing growth and productivity (Wheeler and Von Braun, 2013). Elevated temperatures can also impact respiration rates, water and nutrient availability and uptake, and plant–pollinator interactions, affecting plant growth, yield, and reproductive success. It is important to note that the specific responses of plants to increased temperatures vary among species, genotypes, and environmental conditions (Zandalinas et al., 2018).

Drought, an abiotic factor driven primarily by climatic factors such as reduced rainfall and increased evapotranspiration, can lead to soil moisture depletion. Electromagnetic radiation, including visible light and near-infrared radiation, does not directly cause soil moisture loss or contribute to drought. However, gamma radiation is a powerful tool for controlling abiotic stresses such as drought and salt (Falahati et al., 2007) and can safely induce genetic mutations that can enhance plant stress tolerance (Hwang et al., 2020). However, it is important to conduct such treatments responsibly, following safety protocols to minimize potential risks. Pretreating common vetch seedlings with low-dose gamma radiation increased their salt and drought stress resistance by boosting chlorophyll concentration while decreasing MDA

content (Beyaz, 2020).

3. EMFs for sustainable agriculture

The EMF can potentially improve plant growth and secure food production for the increasing human population. We discussed in our review that the intensity, duration, and species of EMFs impact plant growth. EMFs can also reduce pests and disease-causing plant organisms, allowing greater crop yields. EMFs can also increase nutrient and water efficiency, resulting in more efficient resource use. By enhancing organic matter decomposition, EMFs can also reduce the need for chemical fertilizers and pesticides, making food production more sustainable and environmentally friendly. Reducing the use of chemical fertilizers and pesticides in industrial agriculture minimizes its environmental impact. Furthermore, by stimulating growth factors, EMF can help plants grow faster and more efficiently, increasing yield.

More research has recently focused on the effects of electromagnetic waves, magnetic fields, ultrasound, and ionizing radiation on seed vigor, germination responses, and seedling growth (Rifna et al., 2019). Electromagnetic radiation has developed into an innovative method of priming seeds, with ionizing and microwave treatments proving the most effective. Studies have shown that UV-C and UV-A radiation improve seed germination and seedling vigor in various crop plants, and that low-dose gamma radiation accelerates the germination cycle and enhances seedling growth in lettuce and barley. Similarly, Seed germination and growth in crops such as wheat, barley, and rye could be improved by MWR. The effects depend on species, seed moisture content, seed size, environmental factors during seed imbibition, and electromagnetic radiation exposure, duration, and intensity. Microwave electromagnetic radiation increases seed germination by reducing or changing chemical reactions (Rifna et al., 2019). Studies have also demonstrated that priming can reduce water needs to germinate seeds. Thus, priming seeds with EMF offers a promising alternative to traditional methods. Further, EMF can be used to cultivate food in places where cultivation has previously been difficult (Fig. 1).

4. Future perspectives on the use of EMFs in sustainable agriculture

Using electromagnetic fields (EMFs), such as radiation, microwave, and infrared, in sustainable agriculture holds great potential for improving resource use efficiency, environmental protection, and system resilience. The technology has already shown promising results in various physiological and biochemical aspects of plant growth and development. However, the underlying mechanisms for the stimulatory effects of EMFs are not fully understood, with further investigations needed to explore biochemical and molecular aspects, along with the appropriate dosages and exposure levels for different plant species, as higher doses and long-term radiation exposure may cause damaging

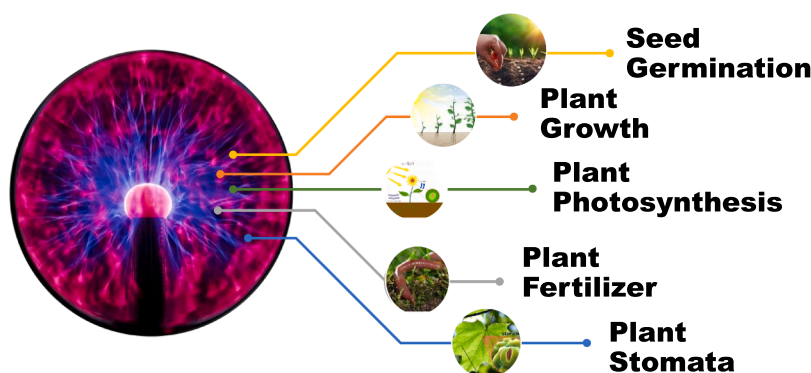


Fig. 2. Impact of electromagnetic waves on plant ecophysiological parameters.

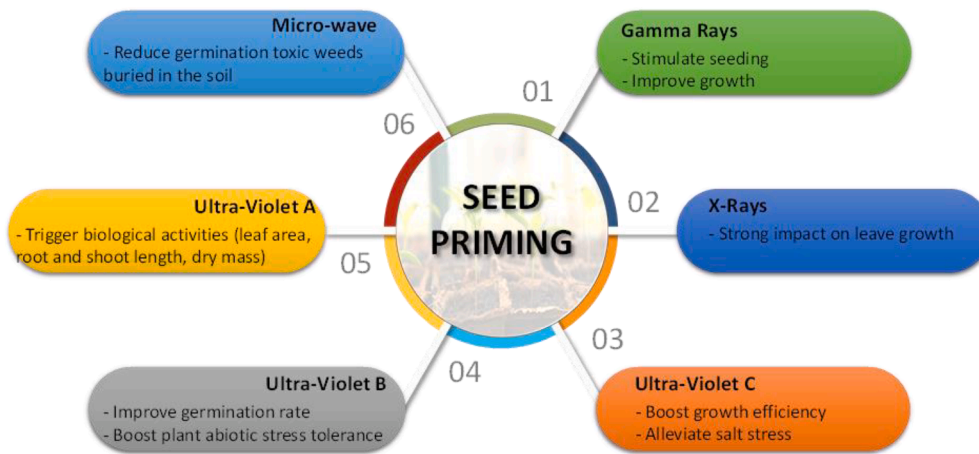


Fig. 3. Application of different electromagnetic radiations and seed priming on plant performance.

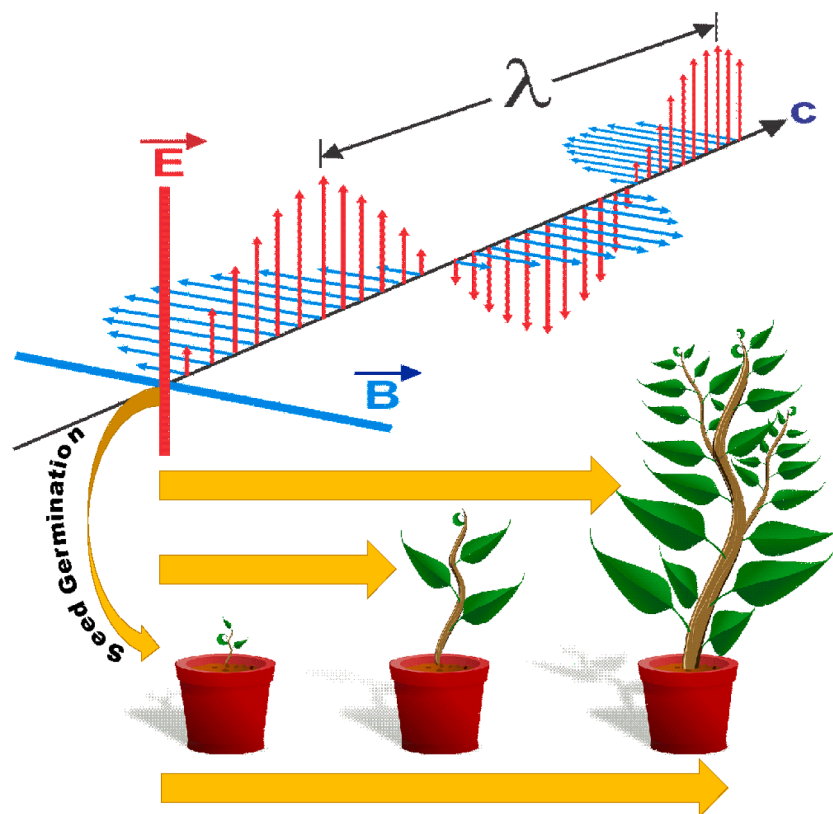


Fig. 4. Electromagnetic field radiations and their interactive effects on plant development.

effects. Numerous reports on seed or plant radiation with UV rays, gamma rays, ultrasound, and ionizing radiation have shown distinct effects on the growth and development of plants, but defining treatment methods and replicating results is crucial for the development of reliable and cost-effective tools to gather information on plant responses to electromagnetic radiation. It is important to be cautious when conducting research on EMFs in agriculture, as biological systems are susceptible to radiation. Preventive measures must be taken to ensure the safety and well-being of plants and the environment. This will involve a multi-disciplinary approach, bringing together agronomists, plant scientists, farmers, ecologists, industrialists, policymakers, and social scientists to collaborate on research, development, and implementation of EMF technology in sustainable agriculture. By fostering

collaboration and continuing research efforts, the future of EMFs in sustainable agriculture looks promising. The technology has the potential to contribute significantly to developing economically viable, environmentally friendly, and socially sustainable farming systems, ultimately helping to address the challenges of feeding a growing global population while minimizing negative impacts on the planet.

5. Pitfalls and precautions of using electromagnetic field radiation for plant cultivation

While electromagnetic radiation has many benefits in our daily lives, it is crucial to be aware of the pitfalls and take necessary precautions to mitigate potential risks. Human exposure to electromagnetic radiation

can cause tumors, psychiatric illnesses, neurological diseases, child anomalies, and cardiovascular conditions. One study reported that residents who live near antennas and cellular towers are prone to severe complications such as anxiety, skin issues, hearing loss, impatience, cardiovascular disease, and sight disturbances (Subhan et al., 2018). In addition to human health concerns, electromagnetic radiation can negatively impact plant development and growth. Microwave processing can impact the nutritional potential of vegetables (Song and Milner 2001). Radiation exposure can impact seedlings, plant weight, development, and stem thickness (Gondal et al., 2023). Ultraviolet radiation can have beneficial and harmful consequences, and overexposure can lead to negative health effects. Furthermore, RF-EMR exposure can disrupt nerve cell function, which may result in abnormal behavior or death (Narayanan et al., 2019).

5.1. Precautions

Some precautionary measures for mitigating the potential safety risks of electromagnetic radiation include:

- 1 Minimizing exposure time and distance to electromagnetic radiation sources. The overall exposure, exposure intensity, and the nature of the radiation play a role in the response.
- 2 Using low power density in electromagnetic transceiver towers located near residential buildings, schools, hospitals, office buildings, and visitor sites to reduce the impact on human health.
- 3 Increasing public awareness of the adverse effects of long-term electromagnetic radiation risks.
- 4 Recognizing that the long-term risk effects depend on the overall dose and length of exposure.
- 5 Taking additional precautionary steps to minimize risk factors associated with MWR exposure, such as reducing exposure time per day and avoiding overuse of microwaves near the human body.
- 6 Understanding that the long-term effects of electromagnetic radiation on living beings can lead to various diseases.

Ensuring that workers installing microwave technology wear insulating shoes, gloves, and protective apparel to minimize exposure.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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