



Review on the impact of cell phone radiation effects on green plants

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Abstract The aim of this review is to assess the impact of cell phone radiation effects on green plants. Rapid progress in networking and communication systems has introduced frequency- and amplitude-modulated technologies to the world with higher allowed bands and greater speed by using high-powered radio generators, which facilitate high definition connectivity, rapid transfer of larger data files, and quick multiple accesses. These cause frequent exposure of cellular radiation to the biological world from a number of sources. Key factors like a range of frequencies, time durations, power densities, and electric fields were found to have differential impacts on the growth and development of green plants. As far as the effects on green plants are concerned in

this review, alterations in their morphological characteristics like overall growth, canopy density, and pigmentation to physiological variations like chlorophyll fluorescence and change in membrane potential etc. have been found to be affected by cellular radiation. On the other hand, elevated oxidative status of the cell, macromolecular damage, and lipid peroxidation have been found frequently. On the chromosomal level, micronuclei formation, spindle detachments, and increased mitotic indexes etc. have been noticed. Transcription factors were found to be overexpressed in many cases due to the cellular radiation impact, which shows effects at the molecular level.

Keywords Electromagnetic field · Enzyme activity · Radio waves · Reactive oxygen species · Specific absorption rate · Transcription factors

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Introduction

Radiofrequency radiation (RFR), a kind of electromagnetic field (EMF) having low frequency and energy, exists in our surroundings as a result of planetary activity, solar actions (Griebmeier et al., 2011; Kerr, 2012), and wireless telecommunicating systems. Radio waves emanating from the natural sources rarely enter into our environment as phenomena like absorption, reflection, and diffraction hinder them at ionosphere (Atnafu et al., 2016). In contrast to that, the radio waves coming from the

networking systems like RADAR (radio detection and ranging), satellites, and cell phones predominate in our environment. RADAR and satellites use very low frequency waves for long range transmission and some of their signals also get attenuated by the ionosphere. But cellular systems being operated nearer to the ground level with radio waves traveling horizontally to the earth's surface contribute to the majority of RFR exposure in the environment and on living beings.

Frequency range of radio waves lies in between very low frequency (VLF) of 3 kHz (kilohertz) and extremely high frequency (EHF) of 300 GHz (gigahertz). Likewise, the wavelength of RFR is so long, ranging from some millimeters to kilometers, which help them travel up to very long distances. Besides that, how far a radio wave will travel depends upon the input power to that signal. As RFR is an EMF wave, it has two components, one is electric field ($\vec{E}$) and another magnetic field ($\vec{B}$). Change in the fields can also affect the properties of a radio wave. Radio waves travel in the air and vacuum and through different materials. It can travel so long without any obstacles in its traveling path. Once any obstacles come, it gets attenuated and experiences some signal loss (Straub, 2017). Higher frequency radiations in comparison to lower ones tend to be more directional. Any materials including biological ones if comes in that path get affected by the properties of radio waves (Vorst et al., 2006). There are three types of radio waves that exist according to the area and mode of propagation, like (i) sky waves, (ii) ground waves, and (iii) space waves (Saakian, 2020). Details of which are given below:

- (i) Sky waves usually get propagated while communicating with satellites or a beam of high-frequency directional waves traveling towards the sky, which travel for a very long distance and again sent back to the environment after being reflected by the ionosphere as per the principle of total internal reflection. These radiations hardly cause any threat to the environment.
- (ii) Ground waves with high-frequency signals travel horizontally to the ground by line of sight action. Low-frequency waves travel in multidirectional path and get affected

by the earth's magnetic field. These waves again reflected back and received by the receiver antennas cause additional radio wave propagation in the environment. Most of the radio waves present in our environment are contributed by these activities. AM (amplitude modulation), FM (frequency modulation), cellular network system and televisions (TVs) etc. contribute to these waves.

- (iii) Space wave travels through line-of-sight (LOS) action, means both transmitters and receivers should face each other in order to establish proper connection. They solely depend on this method to communicate. Satellites and RADAR use this technology in establishing communication between them. Very few radio waves from this category interfere with the environment.

Cellular RF propagation

Cellular towers irradiate radio signals through transmitting antennas, which is received by cellular devices and sent back to the receiving antennas. A typical cellular tower is about 15–50 m high in a macro-cellular unit. Multiple directional antennas or a single omnidirectional antenna gets mounted on the respective towers. A microcellular unit can be operated through less height antennas for a short coverage area. The power generation system having multiple radio transmitters, which is typically a base station, generates power in maximum (P_{tx}). Then, the total output power of an antenna is expressed as,

$$P_{ant} = NP_{tx} 10^{-L/10} \text{ (Seybold, 2005)}$$

Where N =number of transmitters, and L =loss of signal traveling from wire to antenna.

Strength of the signal (S) or the power density decreases with the increase in distance from cell tower to away according to inverse square law and is expressed as,

$$S = (NP_{tx}/4\pi d^2) \times 10^{(G-L)/10} \text{ (Seybold, 2005)}$$

Where d =distance, and G =gain of antenna.

Gain of antenna decides the level of focus of an antenna in a particular direction.

Technological evolution, requirement of higher data transfer speed, downloading efficiency, more reliability, and capability lead to the development in

the field of cellular radio communication technology. In the beginning period at 1980, when first-generation (1G) network was used, only voice call was possible. Less area coverage and low voice quality were the drawbacks of this system. Then, gradually at 1990, the digital system gets introduced, which enhanced voice quality, and started the SMS (short message service). Two main standards of 2G (second generation) were GSM (global system for mobile communications) and CDMA (code division multiple access). Then, after the improved voice quality, there was the requirement of data speed, internet browsing, video calling, and multimedia messaging, which lead to the development of 3G (third-generation) network system at early 2000s. It used UMTS (universal mobile telecommunication service) and CDMA technology for the general operation. There was still requirement of higher data speeds, which lead to the improvement of older technology to a newer fourth-generation network which improved data transfer rate, provided with low latency and high capability. 4G (fourth generation) used LTE (long-term evolution) technology, which facilitated gaming, high-definition mobile streaming, and broadband system. Then, came fifth-generation (5G) technology in 2015, which was provided with ultra-low latency, higher accessibility, and connectivity, which were operated by MIMO (multiple input and multiple output) and mm wave (millimeter wave). Augmented reality (AR), virtual reality (VR), and Internet of Things (IOTs) were being supported in this network. It has been provided in Table 1.

Challenges of upcoming 5G technology

The frequency at which 5G technology operates will be greater gigahertz. High bandwidth and reduced latency are two more innovations in the impending 5G technology. Using orthogonal frequency division access, additional subscribers are able to join the network. Studies on the possible health implications of electromagnetic field exposure related to 5G technology have been conducted. On the other hand, most research indicates that the exposure levels are below the advised safety limits. Nevertheless, research is still being done to evaluate any potential long-term health effects (Russell, 2018). There might be an impact on the environment from the installation of more 5G equipment, such as base stations and tiny cells. Increasing energy usage and the effects of producing and discarding new electronic devices are some issues (Mihailovic et al., 2020).

Electromagnetic spectrum and its effect on biological world

Variable electric and magnetic field creates electromagnetic wave. It can be propagated both in closed system and in free space. It travels from one medium to another by reflection, absorption, and transmission method. Reflected waves superimpose with incident wave and create standing wave. The energy of the wave depends upon the source of the excitation, medium they travel, and frequency of the incident radiation (Guru & Hiziroglu, 2009). Higher

Table 1 Evolution of cell phone technology over the years (Alsharif & Nordin, 2017)

Technology	Bandwidth	Standards	Multiple access	Starting year	Frequency
1G	1.9 Kbps	AMPS (advanced mobile phone system), CDPD (cellular digital packet data), TACS (total access communication system), ETACS (extended total access communication system)	FDMA	1970–1984	800–900 MHz
2G	14.4–384 Kbps	GSM, GPRS (general packet radio service), EDGE (enhanced data for GSM evolution)	TDMA (time division multiple access) and CDMA	1990	850–1950 MHz
3G	2 Mbps	WCDMA, CDMA 2000	CDMA	2001	1.6–2.5 GHz
4G	2 Mbps–1 Gbps	OFDM, Network-LMPS (location management problems)	CDMA	2010	2–8 GHz
5G	1 Gbps <	CDMA and BDMA (beam division multiple access)	CDMA and BDMA	2015	> 6 GHz

frequency radiations like X-rays and gamma rays have higher energy, whereas low-frequency radiations like RFR and microwave have less energy and penetrating capacity. A detailed diagram of electromagnetic wave is given in Fig. 1.

a.) Effect of electromagnetic filed radiation on mammals

Ionizing radiation can cause various types of DNA (deoxyribonucleic acid) damage, including single-strand breaks, double-strand breaks, and base damage in mammalian cells (Goodhead, 1994). Frequent exchange of sister chromatids has been seen in Chinese hamster ovary (CHO) cells exposed to ionizing radiation (Nagasawa & Little, 1992). Acute radiation syndromes, including hematopoietic, gastrointestinal, and neurovascular syndromes, can result from exposure to high doses of ionizing radiation in different age groups of humans (Waselenko et al., 2004). Non-ionizing RFR effects like changes in cell membrane permeability, oxidative stress, and alterations

in gene expression have been found in number of studies done on mammals (Vijayalaxmi & Prihoda, 2009; Manna & Ghosh, 2016; Hoyto et al., 2008; Dasdag & Akdag, 2016; Buttiglione et al., 2007). Epidemiological studies investigating the potential association between long-term exposure to RFR and health issues, such as cancer and neurological disorders, have yielded mixed results in animals (Lin et al., 2022). The National Toxicology Program (NTP) conducted a study on the potential carcinogenicity of cell phone RFR in rats and mice, reporting equivocal evidence of carcinogenicity (Feldman, 2018).

b.) Effect of electromagnetic radiation on plants

Reduced CO₂ (carbon dioxide) uptake through leaves has been seen in response to exposed ionizing radiation (Thiede et al., 1995; Ursino, 1973). Increased oxidative stress also has been observed in some plants (El-Beltagi et al., 2011; Macovei et al., 2014; Wi et al., 2007). Elevated cytosolic Ca²⁺ (calcium), ROS (reactive oxygen species)

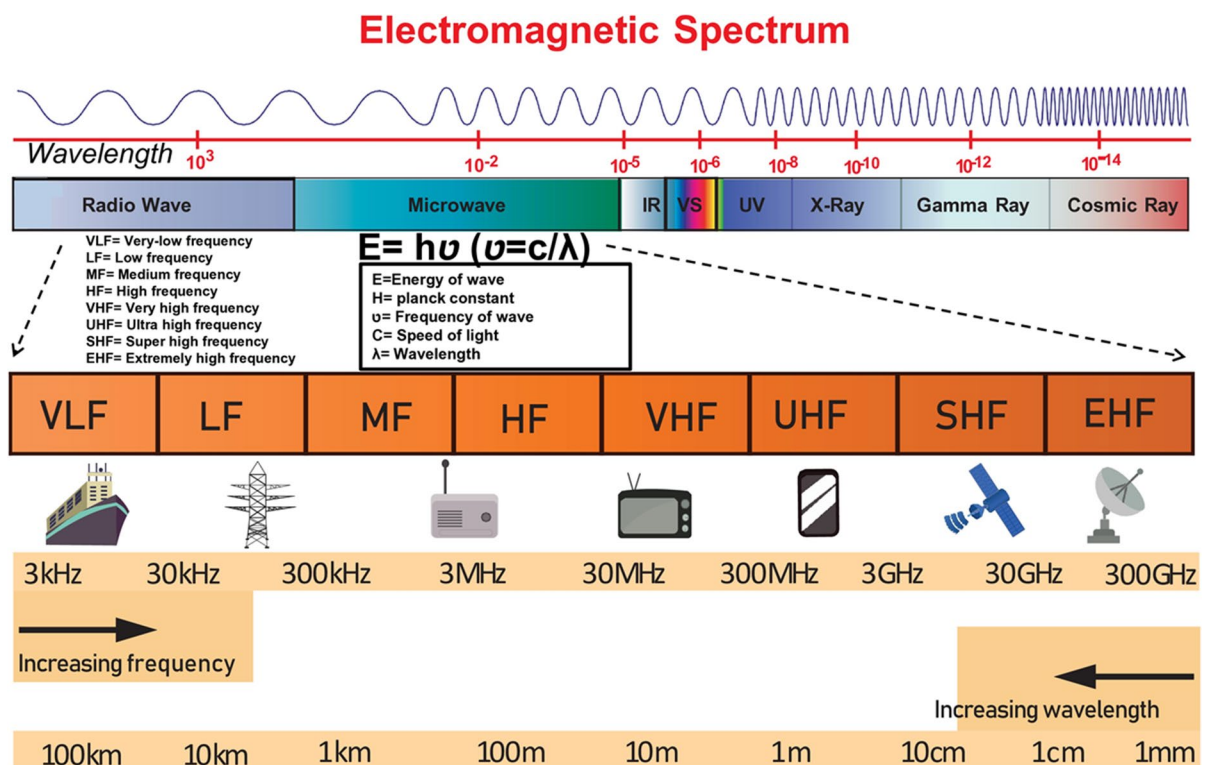


Fig. 1 Electromagnetic spectrum with specific reference to radio wave classification

metabolism, signaling response, and antioxidant defense system activation have been also seen in plants in response to non-ionizing radiation (Kaur et al., 2021)

Effect of cellular RFR on biological world

In spite of the low penetrance and non-ionizing nature, radio waves can cause heating inside the biological tissues and can stay for a longer period of time (Ramaswamy & Tang, 2008). Input power, frequency, and bandwidth decide its extent of severity. Biological entities like plants, animals, and humans continuously being exposed by these radiations are developing hazardous symptoms.

a) Effects of cellular RFR on mammals

There are effects on mammals like ear and eye pains, cognitive disorders (Saikhedkar et al., 2014), changes in cardiac rhythms (Jauchem, 2008), change in muscle contraction patterns (Rafati et al., 2015), increased carcinogenicity (Jargin, 2020), affecting reproductive health (Singh et al., 2018), unusual rise in body temperature (Wyde et al., 2018), and decrease in the number of honeybees (Odemer & Odemer, 2019), sparrows (Balmori & Hallberg, 2007), and birds populations (Balmori, 2005). Other harmful effects on human health also have been found (Celik & Hascalik, 2004; Fragopoulou et al., 2010; Hardell & Carlberg, 2009). Environmental health also has been affected (Pietruszewski et al., 2007; Roux et al., 2006; Sharma & Parihar, 2014). In 2011, the International Agency for Research on Cancer (IARC) declared the cell phone radiation as group-2B radiation, which is possibly carcinogenic to humans.

b) Effects of cellular RF radiation on plants

Effects on plants like the loss in the canopy (Waldmann-selsam et al., 2016), micro-nuclei formation in *Vicia faba* roots (Gustavino et al., 2016), genotoxicity in *Allium cepa* roots (Kumar et al., 2020; Pesnya & Romanovsky, 2013), loss in DNA integrity (Chandel et al., 2019a, 2019b), root oxidation damage and biochemical changes (Sharma et al., 2010, 2009, 2009b), lower biomass production in *Gossypium hirsutum* (Stefi et al., 2017a, 2017b), and alterations

in different physiological parameters have been observed (Pietruszewski et al., 2007; Haggerty, 2010; Kumar et al., 2016).

Specific absorption rate (SAR) value decides how much an animal or plant will absorb these waves. Different boards, councils, and agencies show their concerns and have fixed some guidelines and safety limits to minimize these radiation effects. The permissible SAR level of 1.6 Watts/kg per 1 g tissue has been decided by the Federal Communication Commission (FCC). International commissions on non-ionizing radiation protection (ICNIRP) have set new 2020 guidelines for exposure limits of RFR, which mentioned 5G radiation safety levels, duration of exposure to cause minimum health effects, occupational and general radiation exposure limits, and power density limits (Lemay et al., 2022). The Australian Radiation Protection and Nuclear Safety Agency (ARPNSA) also has set some guidelines to achieve RFR safety standards. The National Radiological Protection Board (NRBP), a public authority in UK (United Kingdom), gets established to carry out research, and advise people and government about ionizing radiation, which later on extended its concerns towards non-ionizing radiation.

96.2% of all people on the planet, including adults and children, currently own a cell phone (ITU, 2015). 1G, 2G, 3G, 4G, and now 5G brought improved technologies like GSM, UMTS, WCDMA (wideband code division multiple access), FDMA (frequency division multiple access), and OFDM (orthogonal frequency division multiplexing) like new technologies, where input power, data transfer rates, and allowed frequency bands were modified, which changed the way of RFR exposed to the environment.

Review of related work on green plants

The effect of electromagnetic RFR on plants is an emerging field. Here, the RFR heating of plant materials can be considered a kind of heating stress. Electrical property of radio waves can be a factor that may affect cellular polarity, membrane function, electron status, and energy status (Kovacic & Somanathan, 2010). Some effects found from manuscripts show damaging, denaturing effects of RFR like oxidative stress (Sharma et al., 2009), lipid peroxidation (Akbal et al., 2012), canopy loss (Waldmann-Selsam et al., 2016), mitotic

instability (Pesnya & Romanovsky, 2013), decrease in chlorophyll content (Kumar et al., 2016), and early senescence (Czerwinski et al. 2023) and other stress responses by plants having strong immunity including increased amylase activity (Chen et al., 2005), enhanced germination (Racuciu & Miclaus, 2007), increased ATP (adenosine triphosphate) level (Roux et al., 2008b), enhancement of enzyme activities (Singh et al., 2012), increased essential oil amount (Soran et al., 2014), and increased secondary metabolites (Upadhyaya et al., 2021). The effects of cellular radiation on plants are given in Table 2. Starting from morphological up to molecular level, the effects have been provided.

The effects of varying frequencies on plant characters is given in Fig. 2, to distinguish plant character that gets affected by which frequency range. In another flow diagram (Fig. 3), the effect of radiation on metabolites has been shown. Starting from primary metabolite to secondary metabolites and smallest amino acids, the effect has been realized. In Fig. 4, the time duration of radiation exposure and its respective effect on plants have been given.

Effect on growth and morphology

The growth and morphology of plants, exposed to RFR, have been found to be significantly affected. Reduction in the number of roots emerged, i.e., about 12% and 32% less, in comparison to control after 0.5 and 2 h of exposures, respectively, seen in mung bean (*Vigna radiata*) seedlings (Singh et al., 2012). In an experiment, by taking two different frequencies, (400 and 900 MHz) and field intensities (23 and 390V/m), in duckweed (*Lemna minor*), it was found that lower frequency radiation affected the plant growth more than the higher frequency radiation. Corn (*Zea mays*) seedlings after being grown in 2.45 GHz Wi-Fi radiation for 1 month showed a significant ($\alpha = 0.05$) increase in height than the control ones (Alattar et al., 2017). Besides that, modulation of frequency caused more effect than un-modulated frequency (Tkalec et al., 2005). Reduction in radicle growth of mung bean (*Vigna radiata*) was found after exposure to 900 MHz modulated RFR, i.e., about 11–59% within just 1–4 h of exposure (Sharma et al., 2010). Exposing

RFR inside the faraday cage by taking aspen seedlings (*Populus tremuloides*), it was found that leaves had no reduction in growth and plants have normal heights. But high necrotic areas with dark, bright red and orange leaves were observed after few days of exposure (Haggerty et al., 2010). In another experiment, by exposing 915 MHz modulated GSM RFR, irradiated *Phaseolus vulgaris* plant was observed with longer trichomes (2–5 times) more than control; in addition to that, dry biomass was found to be increased up to 20% more than control (Surducan et al., 2020). Intermittent exposure of RFR within 1805–1850 MHz for 24 h resulted in reduced height and fresh weight of mung bean (*Vigna radiata*) and hyacinth bean (*Lablab purpureus*) significantly (Chen and Chen, 2014). In response to RFR exposure of 900 MHz in cell phone tower area, the china rose (*Hibiscus rosa-sinensis*) was found to develop less number of flowering buds, i.e., 80.00 ± 9.62 , in comparison to control having 107 ± 15.21 (Oluwajobi et al., 2015). DECT (digital enhanced cordless telecommunication) system, exposing pulsed radiation of 1882 MHz, showed significant reduction of biomass in cotton (*Gossypium hirsutum*) (Stefi et al., 2016). It also induced abnormal structures in epidermal cell and stomata in maize (*Zea mays*) (Stefi et al., 2017a, 2017b). Significant reduction in plant height of tomato (*Lycopersicon esculentum*) was found after being exposed to 1800 MHz frequency of helical antenna. In a study conducted on *Pinus brutia* for 8 months in a field located nearby a cellular base station, a reduction of female cones to 8.82% in a 100-m distant area was seen compared to 100% at an 800-m distant area. Likewise, cone yield was also found to be 13.76% in a 100-m area than 1000% in an 800-m area (Ozel et al., 2021). In exposed plants with 12 h, 60 h, and 120 h of radiation, reductions in plant heights were found, i.e., 18.43 ± 0.60 , 10.40 ± 0.60 , and 9.37 ± 1.46 cm respectively in comparison to control, i.e., 22.17 ± 1.61 cm (Upadhyaya et al., 2022a, 2022b). By exposing different plants to multiple frequencies like 865.71, 866.31, 866.91, and 867.5 MHz modulated waves, late flowering was found in *Trifolium arvense* with exceptional leaf orientation as compared to control and seedling emergence rate was found higher in *Myosotis arvensis*, i.e., 12% than control (Czerwinski et al., 2023).

Table 2 Effects of cellular radiation on green plants

Sl. no	Plant name	Exposure duration	Frequency	Morphological and ultra-structural changes	Cytogenetic changes	Physiological/biochemical response	Molecular changes	References
1	Spruce (<i>Picea abies</i> (L.) Karst.) and beech (<i>Fagus sylvaticus</i> (L.))	3.5 years	2450 MHz			Decrease in foliar cytosolic Ca^{2+} and sulfur level		Schmutz et al. (1996)
2	Flax (<i>Linum usitatissimum</i> L.)	2 h	900 MHz			Disturbances in membrane ionic (Mg^{2+} (magnesium), K^{+} (potassium), Na^{+} (sodium), Ca^{2+} balance)		Tafforeau et al. (2002)
3	Duckweed (<i>Lemna minor</i> L.)	2, 4, 14 h	900 MHz, 1900 MHz	Growth decreased				Tkalec et al. (2005)
4	Woad (<i>Isatis indigotica</i>)	8 s	2450 MHz			Increased enzyme activities of amylase, transaminase, and proteinase		Chen et al. (2005)
5	Alfalfa (<i>Medicago sativa</i>)	7 weeks	2400 MHz	No alternation in morphology, stem length		No alteration in chlorophyll concentration		Skiles (2006)
6	Tomato (<i>Lycopersicon esculentum</i> Mill.)	15 s	900 MHz				Calmodulin, protease inhibitor, and chloroplast mRNA (ribonucleic acid)-binding protein mRNA level increased	Roux et al. (2006)
7	Tomato (<i>Lycopersicon esculentum</i> Mill.)	-	900 MHz				Expression of bZIP (basic leucine zipper) and pin 2 (pin-formed) has been found to be increased	Beaubois et al. (2007)
8	Maize (<i>Zea mays</i> L.)	0.5, 1, 2, 4, 8, 12, 24 h	900 MHz	Increased seedling growth		Enhanced seed germination rate		Racuiu and Miclaus (2007)

Table 2 (continued)

Sl. no	Plant name	Exposure duration	Frequency	Morphological and ultra-structural changes	Cytogenetic changes	Physiological/biochemical response	Molecular changes	References
9	Duckweed (<i>Lemna minor</i> L.)	2, 4 h	900 MHz			Decreased ascorbate peroxidase (APX) activity, increased activity of pyrogallol and catalase enzyme noticed		Tkalec et al. (2007)
10	Tomato (<i>Lycopersicon esculentum</i> Mill.)	10 min	900 MHz			Increased level of ATP concentration and acetylation		Roux et al., (2008a, 2008)
11	Maize (<i>Zea mays</i> L.)	2 weeks	935.2–960.2 MHz	Increased seedling growth		Increased seed germination rate and chlorophyll level		Khalafallah and Sallam (2009)
12	Onion (<i>Allium cepa</i> L.)	2, 4 h	900 MHz	No change in root length	Increased mitotic index and chromosomal abnormality	No change in rate of germination		Tkalec et al. (2009)
13	Common wheat (<i>Triticum aestivum</i>)	5–25 s	2450 MHz			Reduced oxidative stress against salt		Chen et al. (2009)
14	Black gram (<i>Phaseolus aureus</i>)	1, 2, 4 h	900 MHz	Reduced radicle and plumule growth				Sharma et al., (2009, 2009b)
15	Green gram (<i>Vigna radiata</i>)	0.5, 1, 2, 4 h	900 MHz	Decreased root growth		ROS generated oxidative stress, upregulation of antioxidant enzyme		Sharma et al., (2009, 2009b a)
16	<i>Plectranthus</i> spp.	1 h	902 MHz			Activities of the three examined enzymes were reduced for short time period		Kouzmanova et al. (2009)

Table 2 (continued)

Sl. no	Plant name	Exposure duration	Frequency	Morphological and ultra-structural changes	Cytogenetic changes	Physiological/biochemical response	Molecular changes	References
17	<i>Arabidopsis thaliana</i>	24 h	1.9 GHz			Significant change in overexpression of 10 genes		Engelmann et al. (2008)
18	Aspen seedlings (<i>Populus</i> spp.)	8 weeks	1000–3000 MHz	Seedling growth rate was reduced				Haggerty (2010)
19	Peas (<i>Pisum sativum</i> L.)	1, 12, 14 h	947.5 MHz			Change in pattern of chlorophyll fluorescence was observed		Kouzmanova et al. (2010)
20	Mung bean (<i>Vigna radiata</i> (L.) Wileczek)	0.5, 1, 2, 4 h	900 MHz	Reduced length of seedling was observed		The contents of proteins and carbohydrates and rate of germination were decreased significantly		Sharma et al. (2010)
21	Duckweed (<i>Spirodela oligorrhiza</i>)	24 h	1287 MHz			Alanine accumulation was suppressed		Monselesse et al. (2011)
22	Mung bean (<i>Vigna radiata</i>), common wheat (<i>Triticum aestivum</i>)	72 h	900 MHz			Enhanced lipid peroxidation, reduction in protein synthesis, and increased antioxidant enzyme activity		Akbal et al., (2012 b)
23	Lentil, medic seeds (<i>Lens culinaris</i>)	48 h	1800 MHz	Reduction in root growth	Increased mitotic index was observed			Akbal et al., (2012 a)
24	Mung bean (<i>Vigna radiata</i> (L.) Wileczek)	0.5, 1, 2 h	900 MHz	Decreased average root length and numbers		The exposure enhanced the enzyme activities of proteases, polyphenol oxidases, and peroxidases		Singh et al. (2012)

Table 2 (continued)

Sl. no	Plant name	Exposure duration	Frequency	Morphological and ultra-structural changes	Cytogenetic changes	Physiological/biochemical response	Molecular changes	References
25	Rice (<i>Oryza sativa</i> L.)	1, 4, 7, 10 h	2450 MHz			Seed germination was improved		Talei et al. (2013)
26	Onion (<i>Allium cepa</i>)	3 h/day	890–915 MHz		Increased mitotic index, micronucleus, and chromosomal abnormality were observed			Pesnya and Romanovsky (2013)
27	Parsley (<i>Petroselinum crispum</i>), dill (<i>Anethum graveolens</i>), celery (<i>Apium graveolens</i>)	3 weeks	860–910 MHz			Upregulation of terpenoid emissions and modification in essential oil content		Soran et al. (2014)
28	Mung bean (<i>Vigna radiata</i>), red bean (<i>Vigna angularis</i>), soybeans (<i>Glycine max</i>), hyacinth bean (<i>Lablab purpureus</i>)	4–24 h	1800 MHz	Reduction in plant height observed				Chen and chen (2014)
29	Tomato (<i>Lycopersicon esculentum</i>)	10 d	1250 MHz			Increased level of protein accumulation in the cell		Rammal et al. (2014)
30	Roselle plants (<i>Hibiscus sabdariffa</i>)	30 d	900 MHz	Reduction and abscission of flower buds observed				Oluwajobi et al. (2015)
31	Maize (<i>Zea mays</i>)	1–8 h	1000 MHz	Reduced growth rates in plant observed				Racuiu et al. (2015)

Table 2 (continued)

Sl. no	Plant name	Exposure duration	Frequency	Morphological and ultra-structural changes	Cytogenetic changes	Physiological/biochemical response	Molecular changes	References
32	<i>Lepidium sativum</i>	10 d	900–1800 MHz			No germination was seen		Cammaerts and Johansson (2015)
33	Maize (<i>Zea mays</i> L.)	1, 2, 4 h	1800 MHz			The carbohydrate and reducing sugar contents were significantly increased. Chlorophyll content decreased with increased activity of invertases, whereas activity of starch phosphorylases was decreased		Kumar et al. (2016)
34	Soybean (<i>Glycine max</i>)	2 h/5 days	900 MHz	Reduced epicotyl growth				Halganuge et al. (2015)
35	<i>Rosa hybrid</i>		900 MHz	Reduced bud formation was seen. Delayed growth was observed				Gremiaux et al. (2016)
36	Broad bean seedlings (<i>Vicia faba</i> L.)	30 min	915 MHz		Frequent micro-nuclear structures were observed			Gustavino et al. (2016)
37	Multiple plants	6 years		Tree canopies were found to be damaged				Waldmann-Selsam et al. (2016)
38	Corn (<i>Zea mays</i>), basil (<i>Ocimum basilicum</i>), and eggplant (<i>Solanum melongena</i>) seedlings	1 month	2.4 GHz	Increased seedling length		Decreased relative water content (RWC)		Alattar et al. (2017)

Table 2 (continued)

Sl. no	Plant name	Exposure duration	Frequency	Morphological and ultra-structural changes	Cytogenetic changes	Physiological/biochemical response	Molecular changes	References
39	Onion (<i>Allium cepa</i>)	72 h	2100 MHz			H ₂ O ₂ (hydrogen peroxide) accumulation and elevation in superoxide ions		Chandel et al. (2017)
40	Maize (<i>Zea mays</i> L.)	24 h/7 d	1882 MHz	Swelling of chloroplast, undulation, structural deformation				Stefi et al., (2017a, 2017b)
41	<i>Sequoia</i> spp.	1- 6 h	2410 MHz to 2480 MHz	Enhanced root shoot growth		Decreased soluble protein		Halmagyi et al. (2017)
42	<i>Microcystis aeruginosa</i>	1, 2, 4 h	1800 MHz			Photosynthetic protein expression gets adversely affected		Tang et al. (2018)
43	Purple cone flower (<i>Echinacea purpurea</i>)	5–15 min	-			Increased phenolic content, vitamin C level, and radical scavenging activity		Mildaziene et al. (2018)
44	Sunflower (<i>Helianthus annuus</i>)	5 min	-			Reduction in seed germination		Mildažienė et al. (2019)
45	Onion (<i>Allium cepa</i>)	1, 2, 4 h	2350 MHz		High mitotic index value, increased % HDNA (head DNA), and % TDNA (tail DNA) values			Chandel et al., (2019a, 2019b a)
46	Onion (<i>Allium cepa</i>)	1, 2, 4 h	2100 MHz		High mitotic index, % HDNA, and % TDNA			Chandel et al., (2019a, 2019b)

Table 2 (continued)

Sl. no	Plant name	Exposure duration	Frequency	Morphological and ultra-structural changes	Cytogenetic changes	Physiological/biochemical response	Molecular changes	References
47	<i>Pinus brutia</i>	8 months	–	Reduction in male flowers, female flowers, cone yield		Reduced seed germination percentage		Ozel et al. (2021)
48	<i>Withania somnifera</i>	12, 60, 120 h	900 MHz			Induction of secondary metabolite pathway and enhanced antioxidant activity		Upadhyaya et al. (2021)
49	<i>Jasminum grandiflorum</i>	12, 60, 120 h	1800 MHz			Exposed medicinal plants had lower antimicrobial potential than the control group of plants		Upadhyaya et al. (2021)
50	Eggplant (<i>Solanum melongena</i> L.)	12 to 96 h	1800 MHz	Significant decrease in growth was observed in plant height, root length, leaf count, and leaf area		Chlorophyll contents, carotenoid contents, and H ₂ O ₂ contents were modulated as compared to unexposed plants		Upadhyaya et al., (2022a, 2022b)
51	<i>Trifolium arvense</i>	4 months	866–868 MHz	Larger leaf area, altered leaf orientation, larger height		Entered senescence phase earlier during growth phase with less green structures and browning		Czerwiński et al. (2023)

Table 2 (continued)

Sl. no	Plant name	Exposure duration	Frequency	Morphological and ultra-structural changes	Cytogenetic changes	Physiological/biochemical response	Molecular changes	References
52	<i>Arabidopsis thaliana</i>	30, 60 min	2450 MHz			Increased hydrogen peroxide and dehydroascorbic acid content while glutathione, ascorbic acid, and MDA (malonaldehyde) formation remained unchanged		Porcher et al. (2023)
53	<i>Trigonella foenum-graecum</i>	0.5, 1, 2, 4, 8 h	900 MHz		Increased chromosomal aberrations	Increased lipid peroxidation, upregulation of antioxidant enzyme activities of SOD (superoxide dismutase), APX, GST (glutathione S-transferase), POD (peroxidase), and GR (glutathione reductase)		Sharma et al. (2023)

Effect on physiological and biochemical parameters

In response to stress, physiological and biochemical characters get altered, which affect overall plant growth and development. The concentrations of intracellular Ca^{2+} and sulfur (S^{2-}) were found to be reduced, in response to increased power flux density (PFD) and 2450 MHz microwave radiation in beech plant (*Fagus sylvatica*) (Schumtz et al., 1996). A significant increase in the activities of enzymes, i.e., α -amylase (17.2%), total amylase (19.2%), glutamic pyruvic transaminase (17.3%), glutamate oxaloacetate transaminase (8.8%), and proteinase (5.5%), has been reported in *Isatis indigotica* seeds after being exposed to RF radiation of 2450 MHz frequency and 1.26 Mw/mm^2 average power density than control. In tomato (*Lycopersicon esculentum*) plants, radiation exposure of about 900 MHz frequency and low amplitude field intensity of 5V/m for 3 weeks resulted in a decrease in the level of ATP, i.e., 40% less than control (Roux et al., 2008a, 2008b a). In duck weed (*Lemna minor*), exposure to 900 MHz RFR with varying fields like 10 V/m, 23 V/m, 41 V/m, and 120 V/m resulted in elevation of MDA content, i.e., 13–23% than control after 2 h of exposure, and H_2O_2 (hydrogen peroxide) level increased up to 12–34% than control after 2 h of radiation exposure to 400 MHz frequency (Tkalec et al., 2007). Level of antioxidant enzymes also increased like POD (17%), APX (12%),

and catalase (CAT) (45%) than control. Seed germination percentage in maize (*Zea mays*) was enhanced by 50–80%, after being exposed to RF radiation of 935.2–960.2 MHz but in control it was about 30–60% (Khalafallah & Sallam, 2009). By taking rice (*Oryza sativa*), variety MR-219 with 2280–2490 MHz RFR from screw mount dipole antenna, seed germination percentage was found enhanced to 86.7%, whereas in control, it was only 66.7% (Talei et al., 2013). In *Spirodela oligorrhiza*, 1287 MHz and 7.8 V/m RFR source caused decreased amount of alanine production and altered distribution of other two amino acids like glutamine and asparagine ($\text{Glu} < \text{Asn}$), after 2 h of exposure. Some of aromatic plants got selected like dill (*Anethum graveolens*), parsley (*Petroselinum crispum*), and celery (*Apium graveolens*) in order to be studied under RFR exposure of 860–910 MHz GSM frequency and from wireless local area network (WLAN) inside the anechoic chamber. This resulted in an increase in the amount of linalool in dill, i.e., 6.24% than in control and 1.60% in GSM and WLAN respectively (Soran et al., 2014). In tomato (*Lycopersicon esculentum*) plant, 1800 MHz RFR exposure resulted in decreased production of phenol (37.66%), flavonoid (71.38%), and vitamin C (72.45%) with increased production of lycopene (73.13%) (Upadhyaya et al., 2022a, 2022b). Maize (*Zea mays*) plants after being exposed to 1800 MHz modulated RFR for 1, 2, and 4 h resulted in increased activities of

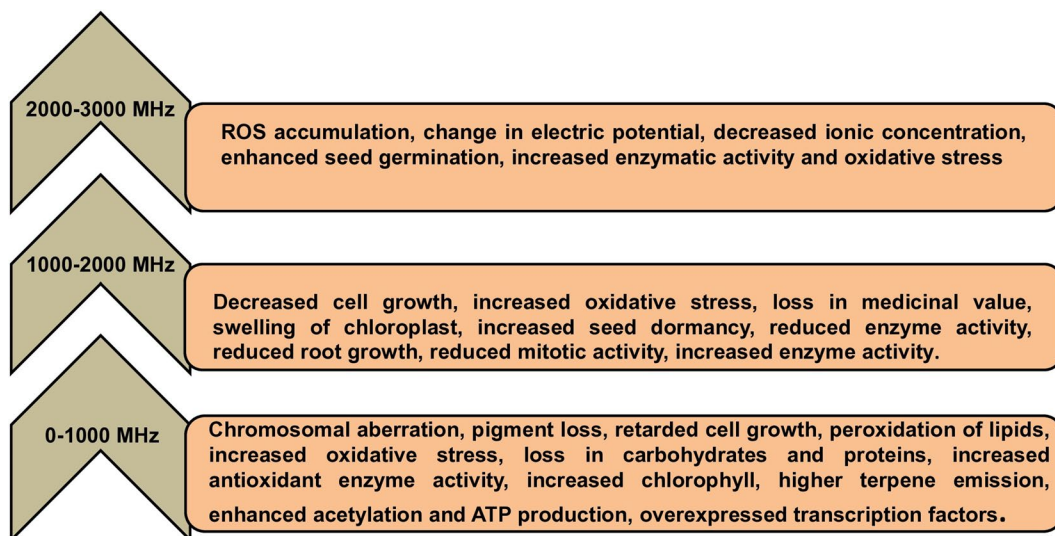


Fig. 2 Response of the plants to various ranges of cellular radiofrequency exposures

enzymes, i.e., starch phosphorylase (36–74%), acid-alkaline invertase (16–82%), and acid phosphatases (16–23%) (Kumar et al., 2016). By taking onion (*Allium cepa*) roots and irradiating it with 2100 MHz RFR, enhancement in MDA production by 23–73% was seen with H_2O_2 level ~5.1 times more in amount and superoxide dismutase (SOD) activity ~1.5 times more than control (Chandel et al., 2017).

Effect on cytogenetics

RFR exposure was found to cause a number of chromosomal aberrations with both cytotoxic and genotoxic effects. After 9 h of exposure by 900 MHz EMF-r, polyploid cells, three-group metaphases, amitoses, and some unspecified abnormalities were detected in *Allium cepa* (Pesnya & Romanovsky, 2013). After being exposed to 915 MHz radiation, frequent micronuclei structures in *Vicia faba* (Gustavino et al., 2016) were observed. About 52% increase in mitotic index was observed in *Lens culinaris* after being exposed to 1800 MHz radiation (Akbal et al., 2012). Experiment done by exposing *Allium cepa* roots to 900 MHz frequency RF energy resulted in high mitotic index, micronucleus structures, and other abnormalities (Tkalec et al., 2009). In another experiment, after

exposing RFR of 2100 MHz for 1–4 h, the formations of laggard chromosome, mitotic bridge, stickiness, fragmented chromosome, and c-mitosis were observed in onion (*Allium cepa*) roots. Besides that, % HDNA was found to be decreased by 22.97% and %TDNA was found to be increased by ~1.76 fold after 4h of exposure. The level of damage or genotoxicity is defined by the amount of the TDNA present. But TM (tail moment) and OTM (olive tail moment) were not seen. All these things are seen in comet assay to check the movements and breaks in DNA to ensure genotoxicity (Chandel et al., 2019a, 2019b). In other experiments conducted on onion (*Allium cepa*) roots by exposing them with 2350 MHz RFR for 1–4 h, increased mitotic index (MI) of about ~2.9% and increased chromosomal aberration up to ~1.4 fold were found compared to control. Likewise, %HDNA was found to be decreased ~2% and ~4.3% in 2 h and 4 h irradiated roots respectively. %TDNA was found to be increased as ~0.3 and ~0.7 folds respectively (Chandel et al., 2019a, 2019b a).

Effect on molecular level

The cellular radiation was found to be impactful in controlling gene expression, transcription factors, and

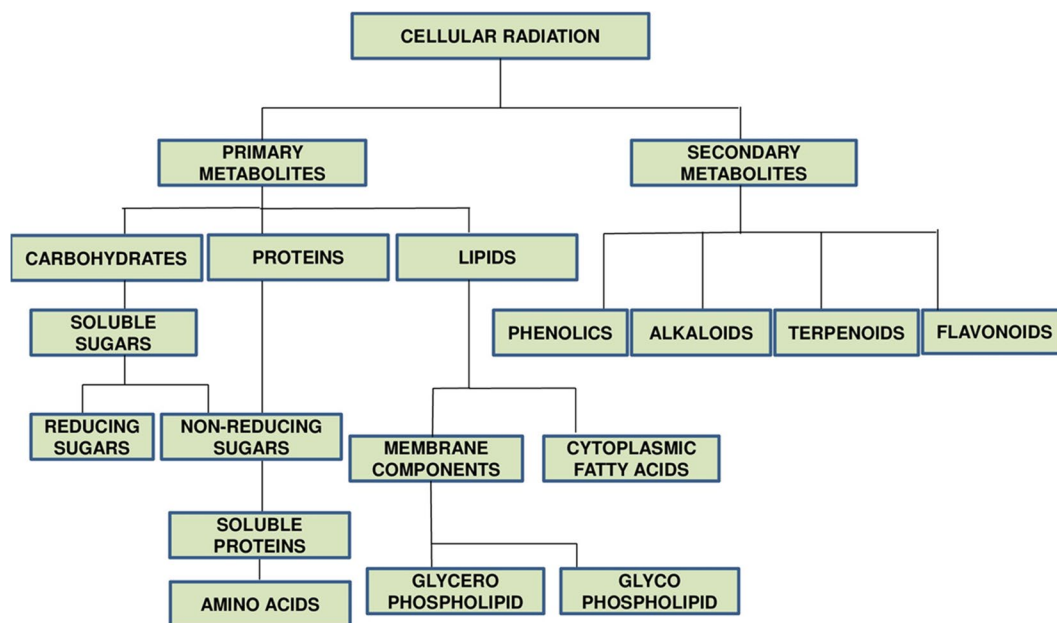
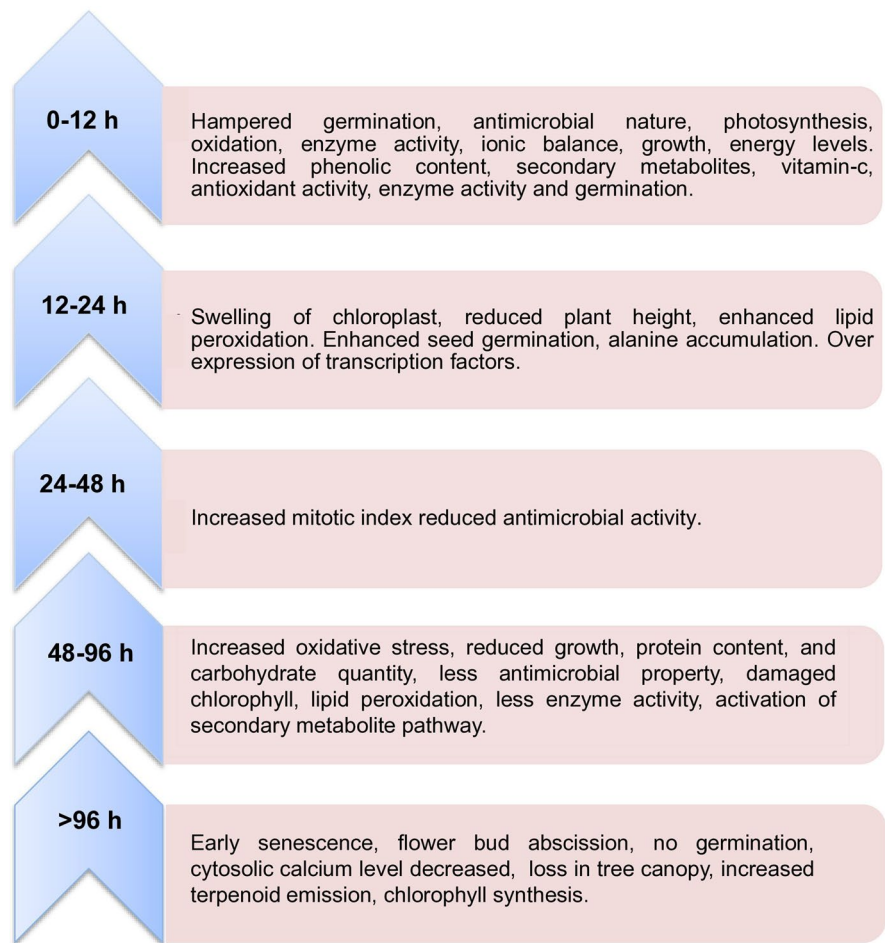


Fig. 3 Different primary and secondary metabolites affected in plants due to cellular radiation

Fig. 4 Response of plants to different time durations of cellular radiofrequency exposure



underlying signaling cascades. The study found that exposure to electromagnetic radiation of 900 MHz of a wild-type tomato plant led to rapid accumulation of (bZIP) in the terminal leaf. In the abscisic acid (ABA) mutant (Sitiens), this response was more rapid but transient. However, Pin2 transcription factor accumulation was less than bZIP in both exposed and control leaves (Beaubois et al., 2007). In another study, tomato plants were subjected to a homogenous and isotropic RFR field (900 MHz) using a mode stirred reverberation chamber. Real-time quantitative PCR (RT-PCR) was used to measure the transcripts associated to stress, including calmodulin, protease inhibitor, and chloroplast mRNA-binding protein. A biphasic response was seen upon exposure to an electromagnetic field, wherein all three transcript levels increased four- to six-folds only after 15 s of exposure (Roux et al., 2006). Affymetrix-ATH1 whole-genome microarrays were hybridized using the mRNA of

exposed cultures and controls in *Arabidopsis thaliana* after being exposed to RF signal of 1.9 GHz throughout the day. Significant transcriptional alterations were found in ten genes using differential expression analysis (Engelmann et al., 2008).

SAR value (Table 3)

The rate at which a body absorbs RFR energy per unit volume is referred to as SAR of that particular body. It represents peculiarity of a biological tissue, which depends upon a number of variables. FCC has set exposure limits and duration to avoid tissue heating and other fatal consequences. Frequency bands and high-power outputs were tested against dummy models of biological tissues. Then, through simulations, the highest SAR value recorded and FCC guidelines were set. ICNIRP is also aware of this value and set exposure dose limits in both occupational and general places.

Table 3 Effect of RF on plants with respect to absorbed power density and SAR value

Sl. no	SAR and power density	Duration	Effects	References
	0.1–0.3 mW cm ⁻² , 1–3 mW cm ⁻² , 10–30 mW cm ⁻²	3.5 years	Changes in intracellular ionic	Schmutz et al. (1996)
	1 mW cm ⁻² , 2W kg ⁻¹	2 h	Misbalance in membrane ionic distribution	Tafforeau et al. (2002)
	0.26, 1.4, 4.45 W m ⁻²	2, 4, and 14 h	Retardation of growth	Tkalec et al. (2005)
	1.26 mW mm ⁻²	8 s	Upregulation in enzyme activity	Chen et al. (2005)
	5, 12 W m ⁻²	7 weeks	No change	Skiles (2006)
	0.95 mW kg ⁻¹ , 0.05 W m ⁻²	0.5, 1, 2, 4, 8, 12, 24, 36 h	Enhanced seed germination rate	Racuciu and Miclaus (2007)
	0.3, 1.4, 4.2, 38.2 W m ⁻²	2, 4 h	Increased antioxidant enzyme activity	Tkalec et al. (2007)
	0.066 W m ⁻²	10 min	Decreased intracellular ATP	Roux et al. (2008a)
	0.7–1.5 W m ⁻²	2 weeks	Increased chlorophyll amount	Khalafallah and Sallam (2009)
	0.3, 1.4, 4.2, and 38.2 W m ⁻²	2, 4 h	Increased mitotic index and chromosomal	Tkalec et al. (2009)
	126 mW mm ⁻²	5–25 s	Reduced stress against salt stress	Chen et al. (2009)
	8.55 μW cm ⁻²	1, 2, 4 h	Decreased protein and carbohydrate content	Sharma et al. (2009b)
	8.55 μW cm ⁻²	0.5, 1, 2, 4 h	Upregulation of antioxidant enzyme	Sharma et al. (2009)
	4.8 W m ⁻² , 2W kg ⁻¹	60 min	Upregulation antioxidant enzyme	Kouzmanova et al. (2009)
	4.8 W m ⁻²	1, 12, 14 h	Change in chlorophyll fluorescence	Kouzmanova et al. (2010)
	8.55 μW cm ⁻²	0.5, 1, 2, 4 h	Decreased protein and carbohydrate level	Sharma et al. (2010)
	0.007, 0.16 W m ⁻²	24 h	Decreased alanine accumulation	Monselise et al. (2011)
	0.76 W kg ⁻¹	48 h	Higher mitotic index, root, shoot growth decreased	Akbal et al. (2012)
	8.54 μW cm ⁻²	0.5, 1, 2 h	Increased PPO enzyme activity	Singh et al. (2012)
	970 μW m ⁻²	6 years	Affected shoot growth	Waldmann-Selsam et al. (2016)
	1.58 mW cm ⁻²	1, 4, 7, 10 h	Delayed seed germination	Talei et al. (2013)
	1.4 W kg ⁻¹ , 4.79 μW m ⁻²	3, 9 h	Increased mitotic index	Pesnya and Romanovsky (2013)
	100 mW m ⁻²	3 weeks	Increased terpenoid emission	Soran et al. (2014)
	0.48–1.45 mW cm ⁻² , 1.0–7.1 W kg ⁻¹	4–24 h	Reduced plant height	Chen and Chen (2014)
	0.47 W kg ⁻¹	1–8 h	Reduced plant growth	Racuciu et al. (2015)
	70–100 μW m ⁻²	10 days	No germination was seen	Cammaerts et al. (2015)
	1.69 W kg ⁻¹ , 332 mW m ⁻²	30 min	Increased total carbohydrate and reducing sugar content	Kumar et al. (2016)
	0.48 μW kg ⁻¹ , 0.049, 0.39, 2.6, 20 mW kg ⁻¹ , 0.1, 11, 86, 560, 4400 mW m ⁻²	10 h	Reduced epicotyl growth	Halgamuge et al. (2015)
	0.00072, 1.15 W kg ⁻¹	90 min	Reduced bud formation, delayed growth was seen	Gremiaux et al. (2016)
	0.4, 1, 1.6 W kg ⁻¹ , 23, 35.2, 46 W m ⁻²	72 h	Occurrence of frequent micronucleus	Gustavino et al. (2016)
	489.7 mW m ⁻² , 2.82 10–1 W kg ⁻¹	1, 2, and 4 h	Up regulated H ₂ O ₂ amount was seen	Chandel et al. (2017)
	7 μW m ⁻²	1–6 h	Decreased soluble protein	Halmagyi et al. (2017)
	0.05 W kg ⁻¹ , 0.08 W kg ⁻¹ , and 0.17 W kg ⁻¹	5, 10, 15 min	Dysfunction in ethylene metabolism Increased flavonoid content	Verma et al. (2020)

Table 3 (continued)

Sl. no	SAR and power density	Duration	Effects	References
	$3.16 \times 10^{-2} \text{ W kg}^{-1}$ and 0.15 W kg^{-1}	12, 60, 120 h	Enhanced lycopene production	Upadhyaya et al., (2022a, 2022b)

Mathematical expression for SAR value:

$$SAR = P/\rho_m = \sigma|E|^2/\rho_m \text{ (Gajsek et al., 2013)}$$

P = Time averaged rate of energy absorbed per unit volume (W/m^3)

ρ_m = Mass density (Kg/m^3) of biological tissue

σ = Electrical conductivity

E = Induced electric field

SAR is integrated with sample volume (per 1g or 10g area).

SI unit of SAR is Watts/kg.

In a study, the maximum temperature rise in the human head and brain is correlated with the peak SAR values caused by cell phone antennas. The Federal Communications Commission standard (1.6 W/kg per 1g) was shown to cause a temperature rise of 0.31°C and 0.13°C . Similarly, they noticed a temperature increase of 0.60 W/kg and 0.25 W/kg for the International Commission on Nonionizing Radiation Protection standard (2.0 W/kg per 10g of tissue) (Hirata et al., 2006). Distance variation affects the SAR value and absorbed power. In a study with a simulation-based approach, about four-fold of increase in SAR value in 0 mm distance has been found than to 1 mm distance and then subsequently a decrease in SAR value with distance (Olteanu, 2013). In another research with UMTS, Wi-Fi, cell phones, and base station uplinks and downlinks, it was found that FBS (False Base Stations) can decrease the SAR levels by 5000 factor (Plets et al., 2014). Nowadays, the SAR values have been determined by powerful tools like FDTD (Finite-Difference Time-Domain) (Rivas & Linares, 2018). In plants, a dielectric probe method has been used to observe variable SAR values in contrast to change in parameters for 2350 MHz and 2450 MHz frequency exposures (Kundu et al., 2021a, 2021b). A hibiscus flower model has been done with simulation to study the change is SAR values (Mukherjee et al., 2020). Again in another experiment, a lily flower model has been done by Mukherjee et al. (2023).

Conclusion

Cellular radiation affects plant seed germination, physiological, biochemical, cytogenetic, and molecular characters. In some cases, the effect has been shown to be positive. There is definitely some impact of these radiations; still there are controversies. Negative impacts can be described as heating stress or charged effect of electric fields, but how the changes are positive nobody explains. Where the positive changes happen or on what frequency, and if power and SAR value is required have not been described. Not much research was found on wild plants, despite having more height and highly exposed in field conditions. Molecular changes in level of mRNA transcriptions have been seen with very less numbers of publications. Changes in the level of ion transports and electron transport chains have been done in very less numbers. Physical absorption and behavior of plant tissues have to be done more widely. The importance of these studies is most crucial because of the increased demand of technology with more number of users and requirement of high-end communication. Vast research in this field is required in order to avoid further hazards.

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Author contribution Dinesh Kumar Panda: writing original draft, editing, conceptualization, figure construction. Debi Prasad Das: mathematical equations, formal analysis, editing, table construction. Santosh Kumar Behera: paper correction, rearrangements, modifications. Nabin Kumar Dhal: whole paper idea, figures, tables, categorization, methodology, and draft writing. All authors read and approved the final paper.

Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

All authors have read, have understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

Competing interests The authors declare no competing interests.

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