



A study on effects of cell phone tower–emitted non-ionizing radiations in an *Allium cepa* test system

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Abstract Considering enormous growth in population, technical advancement, and added reliance on electronic devices leading to adverse health effects, *in situ* simulations were made to evaluate effects of non-ionizing radiations emitted from three cell phone towers (T1, T2, and T3) of frequency bands (800, 1800, 2300 MHz), (900, 1800, 2300 MHz), and (1800 MHz), respectively. Five sites (S1–S5) were selected near cell phone towers exhibiting different power densities. The site with zero power density was considered as control. Effects of radiations were studied on morphology; protein content; antioxidant enzymes like ascorbate peroxidase (APX), superoxide dismutase (SOD), glutathione-S-transferase (GST), guaiacol peroxidase (POD), and glutathione reductase (GR); and genotoxicity using *Allium cepa*. Mean power density ($\mu\text{W}/\text{cm}^2$) was recorded as 1.05, 1.18, 1.6, 2.73, and 12.9 for sites 1, 2, 3, 4, and 5, respectively. A significant change in morphology, root length, fresh weight, and dry weight in *Allium cepa* was observed under the exposure at different sites. Protein content of roots showed significant difference

for samples at all sites while bulbs at sites S4 and S5 when compared to control. Antioxidant activity for root in terms of APX, GST, and POD showed significant changes at S4 and S5 and GR at site S5 and SOD at S1, S2, S3, S4, and S5. Similarly, bulbs showed significant changes at sites S4 and S5 for APX while at sites S3, S4, and S5 for POD and S2, S3, S4, and S5 for SOD and S5 for GR and GST. Genotoxicity study has shown induction of abnormalities at different stages of the cell cycle in *Allium cepa* root tips. The samples under exposure to radiation with maximum power density have shown maximum induction of oxidative stress and genotoxicity.

Keywords Electromagnetic radiations · Antioxidative enzymes · Power density

Introduction

Propagation of energy across space in forms of waves or particles as photons is known as electromagnetic (EM) radiation (Corson et al., 1999; Marjanovic et al., 2012). There are two types of electromagnetic radiation: ionizing radiation and non-ionizing radiation, which can be differentiated based on their capacity to ionize matter (Hyland, 2000). Ionizing radiation is recognized to have an impact on plant and animal bodies, while non-ionizing radiations are far less well understood. Along with human's predominant dependence on various communication channels

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and contemporary technology (number of wireless equipment), exposure to non-ionizing radiations has ascended rapidly (Dasdag & Akdag, 2016; Pesnya & Romanovsky, 2013). The studies examining non-ionizing radiation's impact in living systems have produced differing results where few studies have reported adverse impacts (Sharma et al., 2023; Singh et al., 2012; Upadhyaya et al., 2022), while other studies have reported beneficial effects in terms of growth parameters (Tambiev & Kirikova, 2000; Atak et al., 2003). Different frequency bands have shown to induce oxidative stress responses in various plant test systems (Chandel et al., 2017, 2019).

Many plant bioassays have been designed for exploring the effects of abiotic stress because these assays are inexpensive, are simple to use, and provide a variety of genetic endpoints (Grant, 1999). Various experiments have been performed to study the effects of electromagnetic radiation in various plant systems (Chandel et al., 2019; Sharma et al., 2009; Tkalec et al., 2009). Sharma et al. (2023) studied the long-term exposure effects of EMR at 900-MHz frequency in *Trigonella foenum-graecum* and reported that EMRs at this frequency induced oxidative stress. In a study to explore the comparative cytotoxic and genotoxic effects of a GSM 900 mobile phone containing plutonium-239 alpha particles radiation, Pensya and Romanovsky (2013) reported an increase in mitotic index, frequency of mitosis, and chromosomal aberrations. The increase in frequency of in a time-dependent model was also observed in an *Allium cepa* test system under exposure to GSM 900 radiation. Production of reactive oxygen species in roots of the *Allium cepa* plant when exposed to electromagnetic fields at 2100 MHz was observed during a study conducted by Chandel et al. (2017) where it was concluded that cell phone EMF-r operating at 2100 MHz caused oxidative damage to roots by changing the metabolism of oxidants. A similar study was conducted to explore the effects of EMR at 2350-MHz frequency by Chandel et al. (2019) which reported the genotoxic alterations in *Allium cepa* upon long-term exposure. A study conducted by Alege et al. (2022) suggested that projector radiations were harmful to genetic processes. The results of study showed that, regardless of the time frame of exposure, exposing cells to radiation beyond 20 cm from the projector decreased their ability to cause aberrations and distortion of mitotic cell division cycles. A study on chickpea by Qureshi

et al. (2017) showed that radiofrequency rays were not only genotoxic in terms of induction of micro-nuclei, bi-nuclei, and multi-nuclei, but also carcinogenic as they caused disintegration and ghost cell formation after being exposed for 48 h. Prolonged exposure to non-ionizing, continuous radiation from the base unit of a handheld DECT system induced structural and biochemical impacts on young *Zea mays* plants. Nothing changed regarding the structural aspect, but the chloroplast structure within the bundle sheath cells of the exposed leaves are impacted (Stefi et al., 2017). A study by Upadhyaya et al. (2022) on medicinal plants like Tulsi and Brahmi when exposed to radiations at the frequency at 900 MHz showed an increase in the zone of inhibition for fungal and bacterial strains after 24 h of exposure. The study revealed that radio waves had significant negative effects on antibacterial capacity, affecting both medical systems. A study on *Arabidopsis thaliana* seedling by Senevirathna et al. (2020) upon exposure to radio band microwaves enhanced the photosynthetic pigments, nonphotochemical quenching, hydrogen peroxide content, and fluorescence of the seedlings. Although few studies have been conducted under laboratory conditions to explore the effects of EMRs using different plant systems, no such field study has been conducted to explore the effects of EMRs under different power densities. Observing the rapid rise in the usage of mobile phones and increasing cell phone towers in the city of Amritsar, Punjab, India, the present study was planned to evaluate the effects of cell phone tower-emitted non-ionizing radiations in the *Allium cepa* test system.

Materials and methods

Selection of site

Specific locations with cell phone towers were identified using the Tarang Sanchar portal. The power density ($\mu\text{W}/\text{cm}^2$) at different sites near towers was noted manually using an electromagnetic radiation detector (model: PCE-EM 29; make: PCE instruments, UK). Five sites were selected following the criteria of high-power density exposure and site with convenient experimental setup. Cell phone towers emitting radiations of different frequency bands, viz., 800, 1800, and 2300 MHz, for Reliance Jio 900, 1800 and

2300 MHz for Airtel, and 1800 MHz for Vodafone Idea (VI), were located at the sites of experiment. Depending upon the distance from the cell towers, five sites near towers showed the increasing order of their power density with decreasing distance. Site 1 showed a mean power density of $1.05 \mu\text{W}/\text{cm}^2$ at a distance of 20 m from cell towers, with an angle of $\angle 16.67^\circ$. Meanwhile, site 2 recorded a mean power density of $1.18 \mu\text{W}/\text{cm}^2$ at a distance of 15 m, with an angle of $\angle 21.77^\circ$. Site 3 exhibited a mean power density of $1.6 \mu\text{W}/\text{cm}^2$ at a distance of 10 m and an angle of $\angle 30.94^\circ$. Site 4 showed a mean power density of $2.73 \mu\text{W}/\text{cm}^2$ at a distance of 5 m and an angle of $\angle 50.19^\circ$. In contrast, site 5 displayed a higher mean power density of $12.9 \mu\text{W}/\text{cm}^2$ at distance of 1 m and an angle of $\angle 80.21^\circ$ with an average temperature recorded to be $20\text{--}24^\circ\text{C}$ and relative humidity of $45\text{--}50\%$. The specifics regarding the selection of the exposure sites are provided in Fig. 1. Keeping all other environmental conditions constant and altering only one parameter that is power density, the site with

zero power density is designated as the control at a distance of 50 m and an angle of $\angle 6.818^\circ$.

Experimental setup for EMR exposure

After the selection of sites, an experimental setup was made to expose *Allium cepa* (onion) bulbs to EMRs at variable power densities at sites (1–5). Identical-sized bulbs, purchased from a local market, were placed on Coplin jars containing double-distilled water. The primary, old, and dried roots were scraped with the help of forceps to expose the apices of the root primordia before placing them on water-filled Coplin jars. The bulbs were kept for rooting by dipping their basal parts in distilled water for 3 days (genotoxicity studies) to 7 days (oxidative stress and other morphological studies). For genotoxicity studies, a shorter duration of 72 h was selected because for genotoxicity studies, a sufficient root length (0.5–1 cm) was observed which normally has maximum dividing cells. On the other hand, a duration of 7 days was

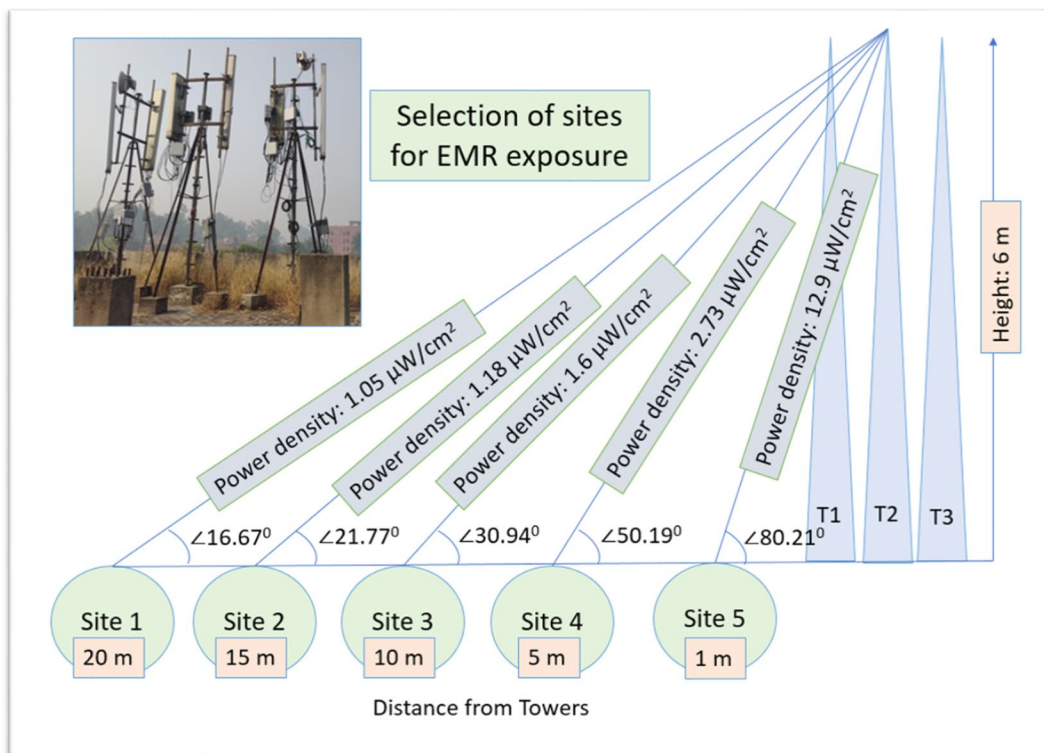


Fig. 1 Various-site selection considering power density and distance from the cell phone towers

selected for oxidative stress and other morphological studies because this extended period likely aimed to allow for a more comprehensive assessment of the oxidative stress response and other morphological changes. Different parameters like root length; fresh weight; dry weight; relative water content for morphological characteristics; antioxidant enzymes such as ascorbate peroxidase (APX), superoxide dismutase (SOD), glutathione-S-transferase (GST), guaiacol peroxidase (POD), and glutathione reductase (GR); and protein content for biochemical studies and percent aberrant (physiological and clastogenic) root tip cells for genotoxicity were observed. Distilled water was added daily to make sure that the base of the bulb was properly immersed in water and root primordia does not dry. For each parameter and exposure site, three separate bulbs were analyzed, constituting a triplicate set. The complete experiment comprised 72 bulbs, with 12 bulbs allocated at each site for a particular parameter. We analyzed a total of six sites, including five exposure sites and one treated as a control. Therefore, the total number of bulbs analyzed for each experimental condition that is morphological root length, fresh and dry weight, and biochemical including protein and antioxidant activity was three for each particular site and parameter, resulting in a comprehensive assessment across five treatment sites and the control group.

Morphological characteristics

After exposing onion bulbs to EMRs at varied power densities at sites 1–5 for 7 days, the roots were separated and different parameters were observed. The root length of *Allium cepa* was measured using a thread and scale. Fresh and dry weights of roots per Coplin jar were determined using a weighing balance (model: CY220; make: Aczet, Mumbai). For fresh weight, the samples were placed on the Whatman filter paper no. 1 to absorb the excess water while for dry weight, roots were dried in a hot-air oven at 60 °C for 5 h or till the weight was stabilized. The relative water content (RWC) was determined by observing the fresh and dry weights of the roots and incorporating the observed values in following Eq. (1).

$$\text{Relative water content} = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Fresh weight}} \times 100 \quad (1)$$

Biochemical studies

Preparation of plant extract

After EMR exposure of *Allium cepa* at varied power densities at sites 1–5 for 7 days, roots and bulbs were separated and immediately brought to the laboratory for preparation of plant extract to be used to measure different biochemical parameters, viz., protein content and antioxidant enzymes. Three bulbs from each site were used for the analysis of each parameter. For preparation of plant tissue extracts, 0.5 g of plant tissues (roots and bulbs, separately) was homogenized in a chilled extraction buffer (50 mM potassium phosphate buffer at pH 7) using pre-chilled pestle and mortar. The homogenate was then centrifuged at 4 °C for 20 min at 8000 rpm. The supernatant was separated, and contents of protein and antioxidant enzyme activity in the resultant supernatant were calculated using different assays as given in the following section.

Protein content analysis

Protein content was estimated using standard Lowry's technique (Lowry et al., 1951). Different concentrations of bovine serum albumin solution were used as standards to create a graph curve for estimation of protein content.

Antioxidant enzyme activity analysis

Different antioxidant enzymes such as ascorbate peroxidase (APX), superoxide dismutase (SOD), glutathione-S-transferase (GST), guaiacol peroxidase (POD), and glutathione reductase (GR) were measured using protocols as mentioned in Table 1.

Allium cepa root bioassay

After exposure to EMRs at varied power densities for 72 h and when roots attained a size of 0.5–1 cm, the root tips were cut and kept in Farmer's fluid (3:1; ethanol: glacial acetic acid) for 24 h (Kumar & Srivastava, 2011). The root tips were shifted to 70% alcohol and stored till further use. The slides were prepared following the squash method where with

Table 1 Protocols for estimation of antioxidant enzymes in roots and bulbs of *Allium cepa*

Enzyme	Reactants	Absorbance	Extinction Coefficient	Reference
Ascorbate peroxidase (APX)	220 µl of 50 mM potassium buffer (pH 7.0) + 30 µl of 0.5 mM ascorbate + 10 µl of 1.0 mM H ₂ O ₂ + 30 µl of 0.1 Mm EDTA, + 10 µl of sample extract	290 nm	2.8 mM ⁻¹ cm ⁻¹	Nakano and Asada (1981)
Glutathione reductase (GR)	200 µl of 50 mM phosphate buffer (pH 7.6) + 30 µl of 1 mM oxidized glutathione + 30 µl of 0.5 mM EDTA + 30 µl of 0.1 mM reduced NADPH + 10 µl of sample extract	340 nm	6.22 mM ⁻¹ cm ⁻¹	Carlberg and Mannervik (1975)
Glutathione-S-transferase (GST)	230 µl of 50 mM phosphate buffer (pH 7.4) + 30 µl of 2 mM of reduced glutathione + 30 µl of 2 mM CDNB + 10 µl of sample extract	340 nm	9.6 × 10 ⁻³ mM ⁻¹ cm ⁻¹	Habig and Jakoby (1981)
Guaiacol peroxidase (POD)	230 µl of 50 mM phosphate buffer (pH 7.0) + 30 µl of 20 mM guaiacol + 30 µl of 12.3 mM H ₂ O ₂ , + 10 µl of sample extract	436 nm	26.6 mM ⁻¹ cm ⁻¹	Sanchez et al. (1995)
Superoxide dismutase (SOD)	170 µl of 50 mM sodium carbonate buffer (pH 10.0) + 30 µl of 0.1 µM hydroxylamine hydrochloride + 10 µl of 24 µM nitro blue tetrazolium dye (NBT) + 10 µl of 0.1 µM EDTA + 30 µl of 0.03% Triton X-100 + 50 µl of enzyme extract	560 nm	-	Kono (1978)

intermittent heating, root tips contained in watch glass were hydrolyzed in 1 N HCl for 1 min followed by shifting them to a watch glass with 9:1 mixture of 2% aceto-orcein stain: 1 N HCl for 30 min. After being stained, root tips were smashed in 45% glacial acetic acid after placing on a glass slide and covering it with a coverslip. The slides were then examined under a microscope (model: MLX-D; make: Magnus) to study various types of physiological and clastogenic abnormalities. At least 500–600 dividing cells per slide were examined for abnormalities at different stages of the cell cycle in *Allium cepa* root tips, and each sample was examined in triplicate. The results of three slides were pooled together

to estimate genotoxicity in terms of percent abnormal cells (inclusive of physiological and clastogenic aberrations) as given in Eq. (2):

$$\text{Percent aberrant cell (\%)} = \frac{\text{Total number of aberrant cells}}{\text{Total number of dividing cells}} \times 100 \quad (2)$$

Statistical analysis

The IBM SPSS Statistics 21 program was used to conduct the statistical analysis. One-way ANOVA was used to evaluate the data followed by the post hoc Dunnet test which was used to compare the means at the significance level ($p \leq 0.05$).

Results

Morphological effects

Different morphological characteristics of *Allium cepa* roots were studied to explore the effects of electromagnetic radiations generated from three cell phone towers by placing an experiment setup at five sites, viz., sites 1, 2, 3, 4, and 5 with varied power densities of $1.05 \mu\text{W}/\text{cm}^2$, $1.18 \mu\text{W}/\text{cm}^2$, $1.6 \mu\text{W}/\text{cm}^2$, $2.73 \mu\text{W}/\text{cm}^2$, and $12.9 \mu\text{W}/\text{cm}^2$, respectively. A site with zero power density was selected as control site. The root length was observed to be decreased for all samples when compared to control. The mean root lengths (cm) were observed to be 5.8, 4.5, 4.2, 3.8, and 2.1 for sites 1, 2, 3, 4, and 5, respectively, as compared to control which was observed as 6.4. Fresh weights (g) were 1.14, 1.05, 0.67, 0.60, and 0.41, and dry weights (g) were 0.06, 0.04, 0.03, 0.03, and 0.01 at sites 1, 2, 3, 4, and 5, respectively, as compared to those of control which were 1.29 g and 0.06 g, respectively (Fig. 2). Post hoc Dunnett test revealed that root lengths showed significant variations ($p \leq 0.05$) for sites 2, 3, 4, and 5 while the fresh weight for site 5 and dry weight for sites 3, 4, and 5 as compared to that of control. All three parameters were observed to be decreased with increasing power density of EMRs.

Relative water content

Relative water content was observed to be decreased for samples at sites 1, 3, and 5 when compared to control while it was slightly increased for samples at sites 2 and 4. However, there was no significant difference ($p \leq 0.05$) observed between relative content

of samples exposed to EMR when compared to that of control following post hoc Dunnett test. Relative water content (%) varied as 94.01 for site 1 with minimum power density ($1.05 \mu\text{W}/\text{cm}^2$) to 95.99 for site 2 with power density of $1.18 \mu\text{W}/\text{cm}^2$. Relative water contents for sites 3, 4, and 5 varied as 94.45%, 95.27%, and 94.23%, respectively.

Biochemical analysis

The effects of cell phone tower-generated non-ionizing radiations on biochemical characteristics were studied in roots and bulb of *Allium cepa* by analyzing protein content and antioxidant enzymes viz., APX, GST, GR, POD, and SOD. The study revealed that protein content was observed to be decreased in both root and bulb samples under exposure to EMR for 7 days when compared to that of control and it was seen that the content of protein was reduced in a dose-dependent manner with increasing power density. For sites 1, 2, 3, 4, and 5, protein content (mg/g of fresh tissue) varied as 0.51 ± 0.003 , 0.5 ± 0.006 , 0.49 ± 0.003 , 0.35 ± 0.001 , and 0.21 ± 0.003 for roots and 0.57 ± 0.007 , 0.57 ± 0.014 , 0.49 ± 0.009 , 0.46 ± 0.022 , and 0.37 ± 0.065 for bulb, respectively. The control sample showed protein contents (mg/g of fresh tissue) as 0.58 (roots) and 0.61 (bulb). Post hoc Dunnett analysis showed significant differences of protein content in roots for all sites while in bulb for sites 4 and 5 as compared to control at a significance level of $p \leq 0.05$ (Fig. 3).

Five different antioxidative enzymes were analyzed to explore the effects of EMR, and results are shown in Fig. 4. It was seen that activities of all the enzymes, viz., APX, GST, GR, POD, and SOD,

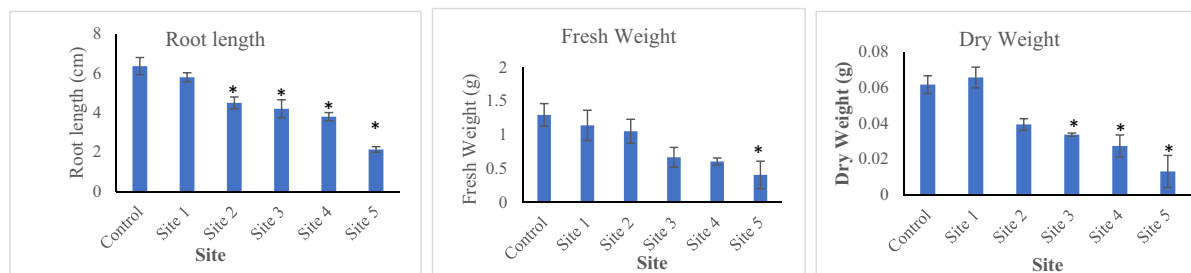


Fig. 2 Root length (cm), fresh weight (g), and dry weight (g) of *Allium cepa* under exposure to EMRs at different sites after 7 days. Significance of the data is determined using post hoc

Dunnett test by comparing the mean value of the control with other treatment groups, * $p \leq 0.05$

Fig. 3 Protein content (mg/g of fresh tissue) of roots and bulbs of *Allium cepa* under exposure to EMRs at different sites after 7 days. Significance of the data is determined using post hoc Dunnett test by comparing the mean value of the control with other treatment groups, $*p \leq 0.05$

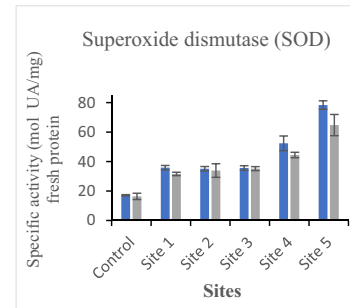
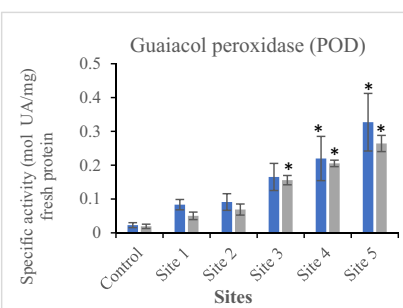
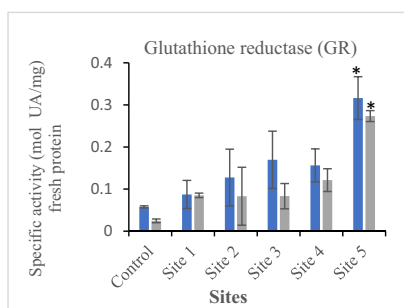
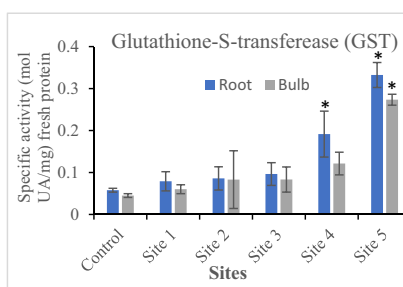
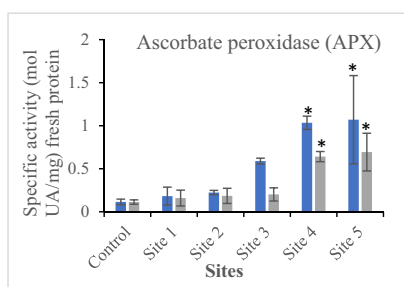
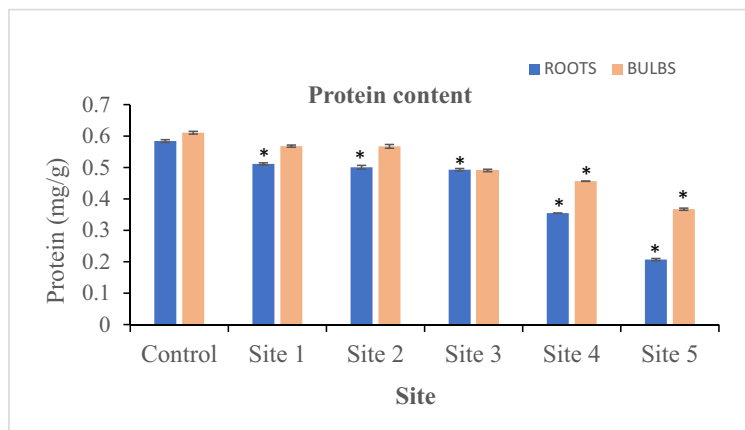


Fig. 4 Antioxidant enzyme activity of roots and bulb of *Allium cepa* under exposure to EMRs at different sites after 7 days. Significance of the data is determined using post hoc

Dunnett test by comparing the mean value of the control with other treatment groups, $*p \leq 0.05$

increased as compared to that of control for both roots and bulb samples of *Allium cepa*. Further, the increase in activities of antioxidant enzymes was observed to be higher for roots as compared to bulbs indicating that roots of *Allium cepa* had higher sensitivity towards exposure to electromagnetic radiations. The specific activity (mol unit activity/mg fresh protein) of different antioxidative enzymes for roots and bulbs of *Allium cepa* with reference to the exposure sites having EMRs with varied power densities (site 1 with minimum power density and site 5

with maximum power density) was observed to be 0.18–1.07 and 0.16–0.69 for APX, 0.08–0.33 and 0.06–0.27 for GST, 0.09–0.32 and 0.08–0.27 for GR, 0.08–0.33 and 0.05–0.26 for POD, and 35.8–78.34 and 31.58–64.75 for SOD, respectively. The control sample has shown specific activity (mol UA/mg fresh protein) of different antioxidant enzymes, viz., APX, GST, GR, POD, and SOD, as 0.11, 0.06, 0.06, 0.02, and 17.14, respectively, for roots and 0.11, 0.04, 0.02, 0.02, and 16.35, respectively, for bulbs. The statistical analysis ($p \leq 0.05$) revealed the specific activities of

APX, GST, and POD to be significantly different for sites 4 and 5 while GR for site 5 and SOD for all sites from that of control values in case of roots. For bulbs, it was observed to be significantly different at sites 3, 4, and 5 for POD; sites 4 and 5 for APX; and sites 2, 3, 4, and 5 for SOD while site 5 for GST and GR as compared to control.

Genotoxicity

The results of present study revealed that subjecting *Allium cepa* root tip cells to 72 h of electromagnetic radiation led to various abnormalities at different stages of the cell cycle. This includes physiological aberrations (c-mitosis, stickiness, vagrants, laggards, delayed anaphase, abnormal anaphase, and abnormal metaphase) and clastogenic aberrations (chromatin bridges, ring chromosome, and chromosomal breaks/fragments) in root tip cells of *Allium cepa* (Table 2; Figs. 5 and 6). Both physiological and clastogenic aberrations were found

to be increased with increasing power density of EMRs. The physiological aberrations (%) varied as 0.33 ± 0.08 , 1.16 ± 0.23 , 1.93 ± 0.25 , 4.21 ± 0.59 , 4.71 ± 0.71 , and 7.84 ± 0.93 , while clastogenic aberrations varied as 0, 0, 0, 0.12 ± 0.08 , 0.70 ± 0.33 , 0.79 ± 0.58 , and 1.74 ± 0.33 for control, site 1, site 2, site 3, site 4, and site 5, respectively. Physiological aberrations were found to be more as compared to clastogenic aberrations indicating that EMRs caused higher damages in terms of spindle fiber disturbances and spindle inhibitions. Among physiological aberrations, abnormal metaphases dominated over other aberrations which were followed by abnormal anaphase, laggard, vagrant, delayed anaphase, and stickiness at the exposure of EMFs at maximum power density at site 5. Similarly, the order of clastogenic aberrations was observed as chromatin bridges > ring chromosome > chromosomal fragments. The genotoxicity studies revealed the potential of EMRs to disturb the genetic integrity of root tip cells of *Allium cepa*.

Table 2 Genotoxic effects of EMRs in *Allium cepa* test system

Types of aberrations	Control	Site 1	Site 2	Site 3	Site 4	Site 5
Physiological aberrations (PA)						
C mitosis	1	3	5	10	10	15
Stickiness	1	2	6	8	6	16
Vagrant	1	1	3	9	8	18
Laggard	0	1	2	9	13	22
Delayed anaphase	1	3	5	8	9	14
Abnormal anaphase	1	6	5	10	8	19
Abnormal metaphase	1	4	6	12	17	13
Total PA	6	20	32	66	71	117
PA (%)	0.33 ± 0.08	1.16 ± 0.23	1.93 ± 0.25	4.21 ± 0.59	4.71 ± 0.71	7.84 ± 0.93
Clastogenic aberrations (CA)						
Chromatin bridge/s	0	0	2	5	8	11
Chromatin Ring	0	0	0	5	3	13
Chromosomal fragments	0	0	0	1	1	2
Total CA	0	0	2	11	12	26
CA (%)	0	0	0.12 ± 0.08	0.70 ± 0.33	0.79 ± 0.58	1.74 ± 0.33
Total aberrant cells (PA + CA)	6	20	34	77	83	143
Total aberration (%)	0.33 ± 0.08	$1.17 \pm 0.23^{**}$	$2.05 \pm 0.24^{**}$	$4.90 \pm 0.66^{**}$	$5.51 \pm 1.19^{**}$	$9.58 \pm 1.24^{**}$
Total dividing cells	1808	1711	1658	1569	1506	1492
Total cells	5550	5510	5500	5520	5480	5500

Significance level was determined using a chi-square test, $^{**}p \leq 0.01$

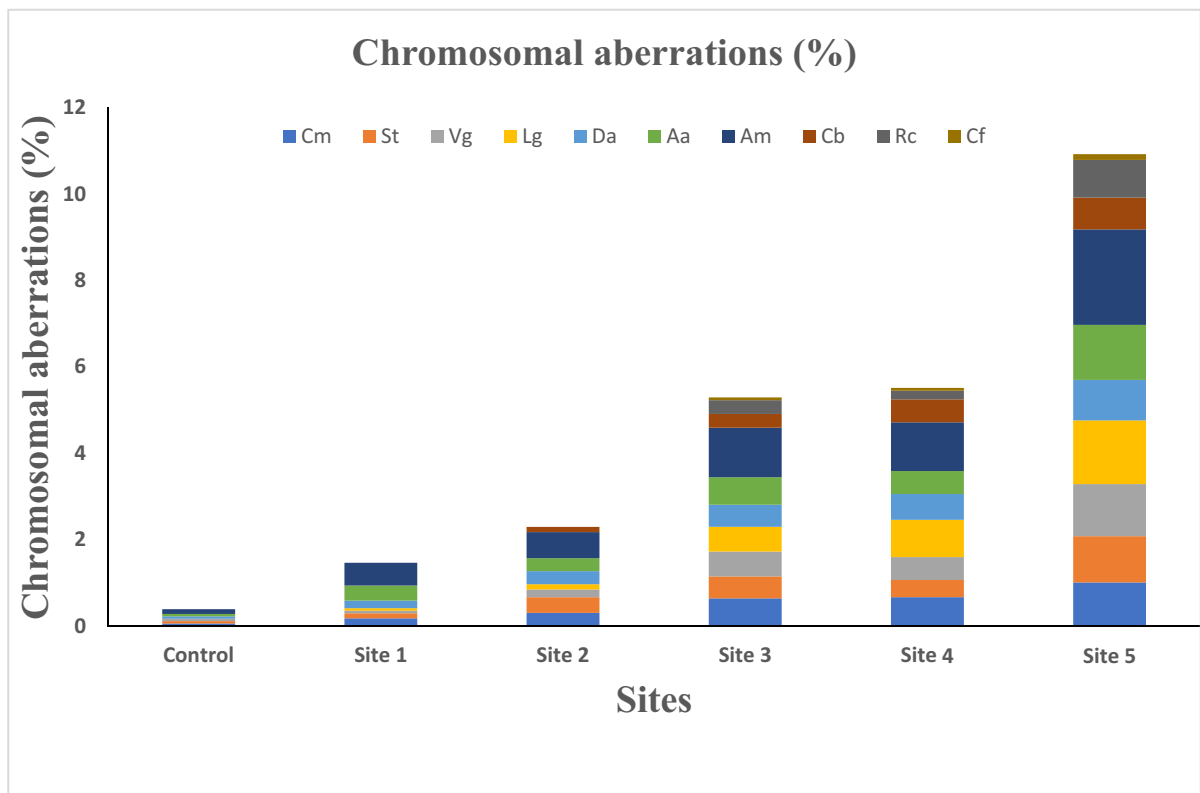


Fig. 5 Spectrum of different chromosomal aberrations induced in *Allium cepa* root tip cells under exposure to EMRs at different sites. C-mitosis (Cm), stickiness (St), vagrant (Vg), laggard

(Lg), delayed anaphase (Da), abnormal anaphase (Aa), abnormal metaphase (Am), chromosomal bridge (Cb), ring chromosome (Rc), chromosomal fragments (Cf)

Discussion

The studies concerning exploration of biological as well as cytogenetic impacts of nonionizing electromagnetic radiations have shown favorable and unfavorable findings (Speit et al., 2007; Sharma et al., 2023). Considering the same, the current study aimed to examine the impacts of in situ simulated radiations emitted from cell phone towers on the *Allium cepa* test system with continuous exposure at different variable power densities. The study revealed that EMRs at higher power density caused morphological and biochemical changes as well as abnormalities at different stages of the cell cycle in *Allium cepa* root tips. The morphological alterations were observed as reduced mean root length (cm) and fresh and dry weights as compared to that of control. However, no significant effect was seen for relative water content. EMR-induced inhibition in root growth and decreased cell elongation were earlier reported by Kumar et al.

(2020) in root tip cells of *Allium cepa*. Reduction in growth parameters of *Withania somnifera* was observed by Upadhyaya et al. (2021) in their study. The present study reveals the harmful effects of EMR exposure at higher power densities. The study is in line with the studies conducted earlier on exploring effects of EMRs in living test systems (Chandel et al., 2019; Kumar et al., 2020; Sharma et al., 2023). The major difference of the earlier studies and present study is that majority of earlier experiments involved growing plant test systems under ex situ conditions with a single frequency exposure while the current study has been conducted in field conditions where EM radiations were from multiple sources and had varied power densities.

Enhanced activity of antioxidant enzymes and reduced content of proteins in roots and bulb samples in comparison to the control during the current study revealed that EMRs induced oxidative stress in the *Allium cepa* test system which further indicated

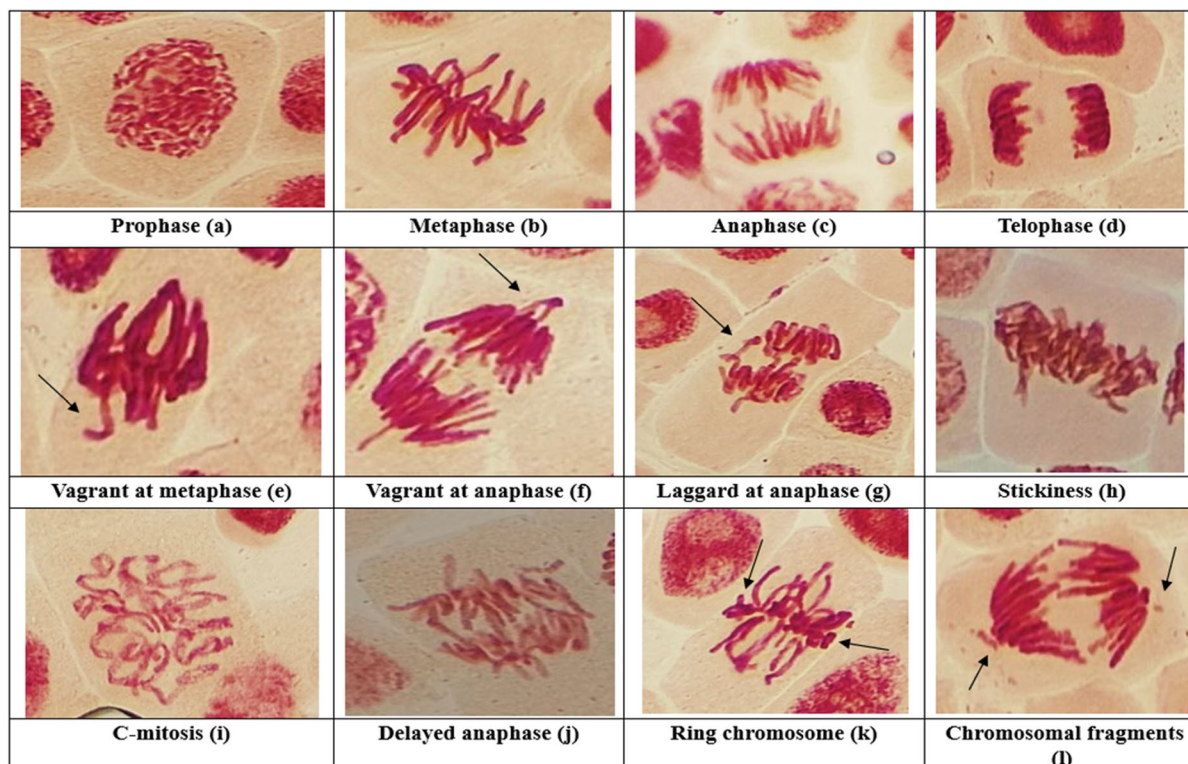


Fig. 6 Different normal stages of mitosis (a–d) and abnormalities at different stages of the cell cycle (physiological (e–j) and clastogenic (k–l) in *Allium cepa* root tip cells under exposure to EMRs at different sites

that enzymes played a protective function against cellular damage that occurred due to exposure to cell phone tower radiations. To evaluate the ability of EMRs to induce antioxidative stress, *Allium cepa* bulbs were kept in continuous exposure of radiations for 7 days at different sites having variable power densities. EMR exposure enhanced the activity of antioxidative enzymes ascorbate peroxidase (APX), glutathione reductase (GR), glutathione-s-transferase (GST), guaiacol peroxidase (POD), and superoxide dismutase (SOD) in roots and bulb of *Allium cepa*. Chandel et al. (2019) conducted a study to explore the effects of electromagnetic radiations at 2100 MHz on roots of *Allium cepa* and found that exposure to EMFs increased the levels of malondialdehyde (MDA), hydrogen peroxide (H_2O_2), and antioxidant enzymes (SOD and CAT). Sharma et al. (2009) also showed during their study that mobile phone radiation (power density: $8.55 \mu W cm^{-2}$; 900-MHz band width; for $\frac{1}{2}$, 1, 2, and 4 h) inhibited root growth in *Vigna radiata* (mung bean) by inducing oxidative

stress. Generation of reactive oxygen species (ROS) in terms of malondialdehyde and hydrogen peroxide (H_2O_2) contents, root oxidizing ability, and changes in levels of antioxidant enzymes were also observed during their study. The cells have a built-in mechanism to combat stress induced by excessive ROS generation, and one such method was reported to increase the release of antioxidant enzymes that captured free radicals (Gill & Tuteja, 2010; Sepehrimanesh et al., 2016). Upadhyaya et al. (2021) reported that EMRs with frequency of 900 MHz at 72 h exposure induced oxidative stress by enhancing various biochemical parameters such as phenolic contents, flavonoids, and total antioxidant activity.

Genotoxicity studies reveal DNA damages or genetic changes which can be carried out employing different plant and animal bioassays. Since plants are more prone to exposures of environmental pollution including radiation pollution, they act as sensitive indicators or bioindicators to reveal the harmful consequences of the same. Among different plant

bioassays, *Allium cepa* root chromosomal aberration assay has been widely validated due to a smaller number of chromosomes ($2n=16$) and larger size. The availability throughout the year and adventitious root system of the plant system further makes it as a convenient test system to carry out genotoxicity studies. The bioassay is based on calculation of frequency of occurrences of aberrations at different stages of the cell cycle including physiological (which occurred due to spindle fiber disturbances) and clastogenic (which occurred due to direct DNA damages). Abnormalities at different stages depict how different living beings after exposure to various physical and chemical pollutants can lead to harmful consequences (De Souza Pohren et al., 2013). In the present study, *Allium cepa* root tip cells upon exposure to EMRs at site 4 and site 5 showed maximum aberrations. Exposure to EMRs resulted in aberrations at various stages of the cell cycle in *Allium cepa* root tips such as physiological aberrations (stickiness, c-mitosis, delayed anaphase, laggard, vagrant, abnormal metaphase, and abnormal anaphase) ascribed to spindle abnormalities and clastogenic aberrations (chromosomal bridge, ring chromosome, and chromatin fragments). A study by Chandel et al. (2019) stated that 2350-MHz radiations induced both cytotoxic and genotoxic effects in *Allium cepa* roots. In comparison to the control, the results obtained for treated samples showed a significantly higher level of mitotic index and chromosomal abnormalities (%) after 4 h and under 2 h of exposure, respectively.

A study conducted by Alege et al. (2022) reported that meristematic cells of *Allium cepa* roots when exposed to projector radiation within a 50-cm range experienced genotoxic effects. Their study further demonstrated that radiation exposure of *Allium cepa* cells within 20 cm of the projector dramatically increased abnormalities at different stages of the cell cycle in *Allium cepa* root tips and altered mitotic cell division cycles regardless of the exposure time. It was reported that distance rather than duration determined the cytogenetic effects of radiations emitted from a projector during their study. To estimate potential harm to DNA (genotoxicity) and carcinogenicity of radiofrequency (RF) radiations on living tissues, a study on dry chickpea seeds was carried out by Qureshi et al. (2017). Seeds of chickpea were exposed to radiation frequency of 900 MHz for 24 and 48 h using GSM cell phones (900 MHz) and laptops

(3.31 GHz), which showed that the percentage of germination for seeds was inhibited by all RF treatments. When compared to the untreated control, the 48-h laptop treatment exhibited the greatest detrimental effects (Qureshi et al., 2017). *Ocimum sanctum* and *Bacopa monnieri*'s increased antibacterial and antifungal activity after 24–48 h of exposure suggests the activation of the plant defense system and a brief favorable effect that could be used going forward to reap the rewards of regulated exposure on medicinal plants. These experimental findings showed that radio waves with high frequencies induced stress in medicinal plants in a way that reduced their capacity to fight with microbes (Upadhyaya et al., 2022).

Conclusion

The present study clearly revealed that plant samples under exposure to electromagnetic radiations generated from cell phone towers at varied frequencies and maximum power densities had altered morphological and biochemical characteristics. The enhanced level of antioxidative enzymes like APX, GST, GR, POD, and SOD during the present study indicate the enhancement of oxidative stress and genotoxicity. The harmful effects of exposure to non-ionizing radiations were also witnessed through reduced protein content in test samples as compared to that of control. The genotoxicity studies revealed that the damage by exposure to radiations was high for root samples as compared to bulb samples indicating that root tip cells of *Allium cepa* were sensitive bioindicators to reveal toxicity of radiation pollution. This study is the first of its kind conducted in the field and reveals that further advance research is the need of an hour for in-depth understanding and devising the effective protective measures for mitigation of the detrimental effects of radiations.

Author contribution Ankita Sharma: Investigation, Conceptualization, Formal analysis, Writing—original draft. Surbhi Sharma: Formal analysis. Shalini Bahel: Resources, review & editing.

Jatinder Kaur: Resources, Supervision, Data curation, Writing—review & editing.

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Data availability Data will be made available on reasonable request.

Declarations

Ethical responsibilities of authors All authors have read, understood and compiled the manuscript.

Ethics approval and consent to participate. No ethical approval is required for present work.

Consent for publication All authors approved the present publication.

Competing interest The authors declare no competing interests.

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