The effect of the non ionizing radiation on exposed, laboratory cultivated upland cotton (Gossypium hirsutum L.) plants

Aikaterina L. Stefi a, Lukas H. Margaritis b, Nikolaos S. Christodoulakis a,∗

a Section of Botany, Faculty of Biology, National and Kapodistrian University of Athens, Ilisia, Athens, 15701, Greece
b Section of Cell Biology & Biophysics, Faculty of Biology, National and Kapodistrian University of Athens, Ilisia, Athens, 15701, Greece

ARTICLE INFO

Article history:
Received 26 June 2016
Received in revised form 15 November 2016
Accepted 15 November 2016
Edited by Alessio Papini
Available online 19 November 2016

Keywords:
Leaf anatomy
Chloroplasts
Root anatomy
Endodermis
Cortex
Cell deformations
Radiation

ABSTRACT

A series of experiments was carried out to investigate possible structural or biochemical alterations in Gossypium hirsutum plants after a long term (21 days) exposure to non ionizing radiation (1882 MHz) emitted from the base unit of a cordless DECT system. Exposed plants, compared to the negative (matched) controls, seem to be seriously affected. Notably lower biomass production for the above ground part and the root was recorded. Reduction of the photosynthetic pigments and severe damage of the chloroplast structure were also observed. It seems that non ionizing radiation can be noxious for plant life functions. © 2016 Elsevier GmbH. All rights reserved.

1. Introduction

It has been reported that the natural radiofrequency environment of the Earth has remained more or less the unaltered within the lifespan of the vivaceous trees since before 1800 (Haggerty, 2010). The major components of this environment were broadband radio noise from space (galactic noise), from lightning (atmospheric noise), and a smaller Radio Frequency (RF) component from the sun. We may assume that the plants have evolved learning to use these environmental signals, along with visible light, in order to regulate their periodic functions. Being sensitive to radiation they may also be sensitive to man-made RF fields (Haggerty, 2010).

Ionizing radiation imposes living organisms to a series of alterations, usually leading to a biological injury (Sax, 1942; Jacobs, 1998; Guilston et al., 2002; Georgakilas et al., 2004; Prasad et al., 2004; Hardell and Carlberg, 2009; Yang et al., 2013). Visible light, UV, X-rays and Gamma rays are electromagnetic (EM) radiations differing in frequency and, consequently, in energy (Kovács and Keresztes, 2002; Ennault et al., 2010).

During the last decade, mobile phones turned to be the most common form of communication. Therefore, the living organisms of the civilized world thrive within a “cloud” of non-ionizing radiations. The rapidly increasing use of the cellular technology resulted in an increase of electromagnetic radiations in the environment (Sharma and Parihar, 2014). Much concern is given to the effects of this radiation to human life (Hardell and Carlberg, 2009; Fragopoulou et al., 2010; Celik and Hascalik, 2004) and environmental health (Roux et al., 2006; Pietruszewski et al., 2007; Sheridan et al., 2010; Sharma and Parihar, 2014). Some concern was given to plant reactions (Ledoigt, 2006; Roux et al., 2006; Pietruszewski et al., 2007; Haggerty, 2010; Kumar et al., 2015) yet only a few data became available, recently, on the biomass production, leaf anatomy and tissue organization, overall for one species (Stefi et al., 2016).

Among the cultivated plants, cotton seems to have global importance. Among the various cotton species Gossypium hirsutum L. (Upland cotton) and G. barbadense L. (Pima cotton) are two of the most important fiber producing cotton species in cultivation. Various cotton species and varieties differ so much in their primary metabolic rates. Even when grown side-by-side in the field they have different photosynthetic and transpiration rates. It is reported that G. hirsutum has the highest rates (Lu et al., 1997). It is also reported that even the bracts and the capsule wall are impor-
tant assimilatory tissues (Wullschleger and Oosterhuis, 1990) even though they present different photosynthetic rates that seem to be related to anatomical differences (Bondada et al., 1994).

Exposure of cotton plants to UV-B radiation reduces the overall canopy size by decreasing plant height, branch length and leaf area without slowing development. Anatomical and morphological changes such as a decrease in leaf thickness, increase in stomatal index, palisade layers and wax content are considered to be adaptive mechanisms for high UV-B radiation (Kakani et al., 2003). Cotton (G. hirsutum L.) plants grown under cool white fluorescent lamps (CWF), whose spectral irradiance includes considerable UV radiation (Pushnik et al., 1987), developed chlorosis, resembling, in appearance, to iron-stress induced chlorosis while plants grown under low pressure sodium lamps (LPS), known by their signature monochromatic yellow color, were not affected at all.

It was also reported that G. hirsutum, varieties appear to be very sensitive to other environmental factors (i.e. ion availability, rain fall, drought), adapting the anatomical features of their leaves (epidermis, palisade and spongy tissues, chloroplast ultrastructure) in such a way as to improve their tolerance (Bhatt and Andal, 1979; Zhao et al., 2001). They seem to respond directly to O3 exposure presenting chlorotic and necrotic patches on their leaves, increased stomatal or epidermal cell density and yellowness of cotton fibers. Moreover, their non-glandular hair density is reduced as well as the plant height, chlorophyll content, net photosynthetic rate, stomatal conductance and length and area of bracts and petals (Zouzoulas et al., 2009).

Therefore, having in mind the effects of the non-ionizing radiation on the delicate, short-lived plants of the model species Arabidopsis thaliana (Stefi et al., 2016) and considering cotton plants as very important for the global economy, we tried to investigate any potential changes in development, biomass yield, leaf structure, leaf-cell ultrastructure, photosynthetic pigment content and other deformations or damages that may appear on young individuals of this particular species of cotton – which is widely cultivated in all suitable Mediterranean areas – after a long term exposure to non ionizing, DECT emitted radiation.

2. Materials and methods

2.1. Plant material and exposure setup

Seeds of Gossypium hirsutum var ST 402 were imbibed and incubated at 25 °C (70% humidity) in the dark. Germinated seeds (3–5 mm radicle protrusion) were transferred and sown in 50 mm Jiffy-7 Peat Pellets (Jiffy Products International B.V. – U.S.A.). Sixteen (8 × 8) Jiffy-7 pellets, with one germinated seed each, were placed in each of the two Faraday cages (40 cm × 40 cm × 25 cm, covered with 0.8 mm mesh – 0.1 mm stainless steel wire) thoroughly checked, after their construction, for their ability to isolate any radiation emitted from within while both cages, being of the Faraday type are radiation proof. Radiation inside and outside both cages during full function of the system was meticulously measured in a previous experiment (Stefi et al., 2016). The cages had a build-in light source (Philips CorePro LED bulb, 11.5 W = 75 W, at 2700 K. 105 mA) producing 2500 lx radiation (Photosynthetically Active Radiation = 60 μmol m⁻² s⁻¹) at the surface of the Jiffies (Fig. 1).

Both cages were placed in a ventilated, adjustable temperature P-Selecta incubator (Model No. 2000238—Barcelona, Spain) where they remained at 20 °C for three weeks (1st experiment). In the middle of one of the two cages, the base unit of a DECT telephone apparatus (General, Model 123) was appropriately positioned. The DECT base was in a 24 h a day, 7 days a week, pulsed transmission mode, at 1882 MHz, as described elsewhere (Margaritis et al., 2014)

Table 1

<table>
<thead>
<tr>
<th>CAGE</th>
<th>Average</th>
<th>Maximum – integrated</th>
<th>Maximum – peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.073 V/m</td>
<td>0.458 V/m</td>
<td>0.490 V/m</td>
</tr>
<tr>
<td>Exposed</td>
<td>2.672 V/m</td>
<td>11.320 V/m</td>
<td>27.460 V/m</td>
</tr>
</tbody>
</table>

while the light/dark programme of the chamber was adjusted to a 16/8 cycle (Stefi et al., 2016). The experiment was repeated once again with identical setup but different temperature, regulated at 30 °C (2nd experiment) (Fig. 2). Incubator temperatures of 20 °C and 30 °C, were selected since germination and growth G. hirsutum is reported to vary depending on temperature with the above temperatures marking the edges of the optimal plant growth (Zang et al., 1990; Krzyzanowski and Delouche, 2011).

Radiation was measured in the two cages, while the DECT device was transmitting within one of them, with a NARDA SRM3000 (Germany) spectrum analyzer. The corresponding electrical field intensity (average and peak), in each experimental setup, was measured for a 6-min period according to ICNIRP (1998) guidelines as in Table 1. Supplementary, low precision measurements were made in the control cage: with a broadband field meter (TES-92, 50 MHz–3.5 GHz, Electromagnetic radiation detector – TES Electrical Electronic Corp. Taipei, Taiwan, R.O.C.) at the value of 490.1 mV/m. In the nearby cage (exposed), radiation reached the value of 27.46 V/m (27.460 mV/m, at 1882 MHz) (55 fold higher).

2.2. Microscopy

At the end of each experiment, the Jiffies were removed from the cages and dispersed in water to remove the plants which were washed to remove any remnants of the culturing substrate from the roots and placed on a filter paper (Figs. 3 and 4) to dry at 60 °C, for three days. All the plants were weighed for their above ground part and their root system. A small part from the centre of a fresh leaf, adjacent to the central nerve, was removed from three leaf taken in random, cut in to small pieces (1 × 1 mm) and fixed in phosphate buffered 3% glutaraldehyde (pH 6.8) at 0 °C for 2 h. A few pieces were dehydrated in graded acetone series, critical point dried, coated with gold and viewed with a JEOL JSM-6360 Scanning Electron Microscope. The rest of the tissue was post fixed in 1% osmium tetroxide in phosphate buffer, dehydrated in graded ethanol series and embedded in Durcupan ACM (Fluka, Steinheim, Switzerland). Semithin sections obtained from a LKB Ultrotome III, were placed on glass slides and stained with 0.5 toluidine blue O (in 1% borax solution), as a general stain, for light microscopic observations. Ultrathin sections were placed on 100 mesh grids, double stained with uranyl acetate and lead citrate (Reynolds, 1963) and viewed with a Phillips EM-300 Transmission Electron Microscope.

The whole procedure was repeated after each one of the two experiments and the embedded tissues were sectioned and observed, for cross-checking the results. Literature for double fixation is cited in detail by Christodoulakis et al. (2009) and Christodoulakis et al. (2010).

2.3. Pigments protocol

Chlorophyll pigments, from approximately 50 mg leaves, were extracted with 1 ml 80% acetone, overnight, at 4 °C. Supernatant was transferred to a 1-ml glass cuvette for measurement in UV/Vis Specol photometer (Zeiss). Absorbance was read at both 663.6 and 646.6 nm, corresponding to chlorophyll - a and chlorophyll - b respectively. Furthermore, absorbance of chlorophyll - c at 625 nm was also obtained. Quantification of pigment content was calculated using molar extinction coeffi-
Figs. 1–4. 1. The two Faraday cages pictured at the end of the 3-week period (1st experiment terminated). The black, DECT base unit is visible inside the right cage. 2. The two Faraday cages pictured at the end of the 3-week period (2nd experiment terminated). The DECT base unit always is in the right cage. 3. The yield at the end of the first experiment. Ungerminated seeds are also exposed. (control plants on the left, exposed plants on the right). 4. The yield at the end of the second experiment. There are only 3 not germinated seeds in the exposed plant group.

Figs. 5–8. Cross section from epoxy embedded leaf tissue, stained with toluidine blue O. Upper couple of figures = 1st experiment. Lower couple of figures = 2nd experiment. 5. Leaf from a control plant. 6. Leaf from an exposed plant. 7. Leaf from a control plant. 8. Leaf from an exposed plant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
3. Results

3.1. Plant morphology and biomass

Initially, the plants were compared morphologically. An interesting observation is that the germinated seeds which failed to develop to young plants were superior in number at the exposed group. Only a few seeds failed to develop in the control cage, at the 1st experiment. None at the 2nd experiment. Comparing the grown plants of the control cage, from the first stages of their life, we observed that they produce more and larger leaves in both experiments. Their exposed counterparts seem to be retarded in growth and their leaves were fewer and smaller (Figs. 3 and 4). The above ground part of all plants (control and exposed) was always heavier than the root. The quantitative approach of the differences in the two cages is given in Table 2 through the values for the dry weight (biomass) of the above ground (stem and leaves) parts, the roots and the germinated seeds that failed to grow, for the two groups, in each of the two experiments.

3.2. Light microscopy

Light microscope observations of semi thin sections from epoxy embedded tissue, revealed that when the amphistomatic leaves of the two groups are compared they present some interesting differences in leaf thickness, development of mesophyll tissues and intercellular space formation (Figs. 5 and 6) in both experiments. The leaves of the control plants were definitely thicker than those of the exposed plants in both experiments. Control leaves in the second experiment (Fig. 7) were more compact and somehow thinner than those of the first (1st exp = 198 ± 22 μm, 2nd exp = 169 ± 14 μm). Exposed leaves of the second experiment (Fig. 8) appeared thinner and more compact, compared to the control ones, and had about the same thickness with their counterparts of the first experiment (1st exp = 125 ± 14 μm, 2nd exp = 127 ± 12 μm). Both leaf types (control and exposed) had a single layer of palisade tissue occupying the same percentage of the mesophyll space yet the exposed leaves (Figs. 6 and 8) were more compact than the control ones (Figs. 5 and 7) in both experiments. No differences could be traced on the single layered epidermis except the smaller cells of the exposed leaves.

An interesting observation has to do with the cotyledons. They appear on the plant as the first pair of photosynthetically active blades and although no structural differences can be traced in these embryonic organs (Figs. 9 and 10) it seems that exposed cotyledons fail to keep their chloroplast equipment equal in number to that of the control ones. The cotyledons were hardly thicker for the control plants (1st exp = 309 ± 21 μm, 2nd exp = 311 ± 17 μm) compared to the exposed ones (1st exp = 306 ± 19 μm, 2nd exp = 310 ± 12 μm).

Observations of cross sections of the primary root, about three millimetres from the root tip, revealed some structural differences concerning the various distinct tissues of the root (Figs. 11 and 12). The cytoplasm in the cortex cells was denser and easily stained in the exposed roots. The cells of the discrete layer of endodermis had thick walls and were lined, outwards, with a layer of cortex cells exhibiting densely stained osmiophilic content. The cells of the pericycle appear larger in size, compared to those at the control roots, in both experiments and in every section of the primary root observed.

3.3. Scanning electron microscopy (SEM)

Concerning the epidermal tissue, Scanning Electron Microscope observations reveal that, when the two leaf types are compared, no distinguishable differences can be traced on the adaxial epidermis (Figs. 13 and 14). On the contrary, observations of the abaxial epi-
Table 2
The values recorded after weighing the dry mass of the plants from the two experiments.

<table>
<thead>
<tr>
<th></th>
<th>after 3 weeks of growth</th>
<th>root</th>
<th>failed to develop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>above ground</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st experiment at 20 °C (14-03–05-2016)</td>
<td>1001.1 ± 12.2 mg</td>
<td>105.1 ± 8.6 mg</td>
<td>393.41 ± 11.2 mg</td>
</tr>
<tr>
<td>control (16 sprouts)</td>
<td>689.3 ± 29.3 mg</td>
<td>42.9 ± 21.9 mg</td>
<td>757.79 ± 19.6 mg</td>
</tr>
<tr>
<td>exposed (16 sprouts)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd experiment at 30 °C (06-04–26-2016)</td>
<td>1753.9 ± 14.9 mg</td>
<td>151.1 ± 11.1 mg</td>
<td>–</td>
</tr>
<tr>
<td>control (16 sprouts)</td>
<td>1155.7 ± 31.2 mg</td>
<td>103.5 ± 19.3 mg</td>
<td>121.8 ± 17.3 mg</td>
</tr>
<tr>
<td>exposed (16 sprouts)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

dermis, reveal noticeable differences on the capitate glandular hair (Figs. 16 and 18) density. The frequency of these trichomes on the abaxial surface of the control leaves was measured at 8 ± 2 mm⁻¹ while this figure rises on the abaxial surface of the exposed leaves reaching the value of 17 ± 3 mm⁻¹ (compare Figs. 15 and 16).

Anomocytic stomata (Fig. 17) appear on both leaf surfaces, more frequently on the abaxial side. No differences in the number, type or magnitude of stomata was observed for the two leaf types.

Concerning the cotyledons, no structural differences can be observed on both surfaces. There are no differences in the number of the equally developed and undisturbed stomata appearing on the adaxial (compare Figs. 19 and 20) and the abaxial surface (Figs. 21 and 22) of the control and the exposed plants in both experiments except that the few trichomes that can be observed on the abaxial side of the cotyledons in treated plants are almost absent from the abaxial side of the control plants (Figs. 23 and 24).

3.4. Transmission electron microscopy (TEM)

3.4.1. Leaves

TEM investigation of ultra-thin leaf sections from epoxy embedded tissue (Figs. 25–28) reveal no major differences in cell
arrangement and structure between control and exposed leaves. The nucleus, plastids and vacuole appear intact in the mesophyll cells of the exposed leaves (Fig. 25). A close look at the nuclear envelope confirms that both membranes, surrounding the nucleus, are intact. Yet, chloroplasts, at high magnifications, seem to differ significantly in the mesophyll cells of the exposed leaves, compared to those in the cells of the control leaves. Chloroplasts from the cells of the control leaves, appear intact in structure with well preserved lamellae and numerous, distinct and well organized grana (Fig. 26). On the contrary, cells of the exposed leaves possess chloroplasts with dark, electron dense stroma, hardly visible membranes and only a few signs of stacks of membranes or distinct grana. They do accumulate starch (Fig. 27) and their envelope seems to have lost its integrity. The same deformations appear in all the chloroplasts from the mesophyll cells of the exposed plants (Fig. 28). Mitochondria appear intact in both types of cells. The infoldings of the inner membrane and the matrix of these organelles do not seem to be affected in the cells of the exposed leaves (red arrows in Figs. 26 and 28).

Microbodies, in general, like peroxisomes and glyoxysomes, do not seem to be disturbed and appear intimately associated with other organelles, as expected. Peroxisomes, in particular, appear intact and always associated with mitochondria or chloroplasts.

3.4.2. Roots

Ultra-thin sections from epoxy embedded roots (Figs. 29–32) investigated with TEM, confirmed the LM observations and gave interesting details. Observations focused on the endodermal cells and the pericycle of the primary root. Endodermis (marked as end in Figs. 29 and 30), being the innermost cell group of the root cortex, can easily be distinguished from the magnitude and the regular arrangement of its cells. Just bellow the endodermis, within the central cylinder, lays the pericycle (marked as per in Figs. 29 and 30). The cortex cells adjacent to the endodermis, are the key-cells in this observation. In control plants, these cells (yellow arrows in Fig. 29) have a strange shape and appear empty. On
the contrary, the corresponding cells (yellow arrows in Fig. 30), in the roots of the exposed plants, appear to accumulate large quantities of osmiophilic material. Endodermal cells and the cells of the pericycle appear similar in both root types; the endodermal cells in the control plants seeming to have their vacuole lined with a thin layer of electron dense material (Fig. 29).

Subcellular structures like plastids and mitochondria (Figs. 31 and 32), as well as the nucleus (Fig. 32) appear unaffected in these heavily loaded with electron dense metabolites, cortex cells.

3.5. Pigment content

The values for the absorbance of the five major chloroplast pigments from the control and exposed leaves as well as from the respective cotyledons are given in Fig. 33 for both experiments. In both experiments the main photosynthetic pigments were drastically reduced in the leaves of the exposed plants. It seems that the quantity of the pigments was constantly higher in all green parts (leaves and cotyledons) of the control and exposed plants, in the second experiment, compared to the plants of the first experiment. Pigment alterations are statistically negligible for the cotyledons, in both plant groups and both experiments, while a rise in beta-carotene and xanthophyll contents was observed in the leaves and cotyledons of the exposed plants, in both experiments. However, concerning the major photosynthetic plant organs, the leaves, it appears that the reduction of all chlorophylls, in the exposed plants, drops at about fifty percent, which is beyond any statistical argument.

4. Discussion

Our data indicate that Gossypium hirsutum L. plants exposed to radiation appear to have distinct differences from the control ones. These differences concern plant development and terminal crop (biomass for the above ground part and the roots), development of the leaves, root structure, number and structure of chloroplasts and, finally, the photosynthetic pigment content (mainly chlorophylls). Although the short-living cotyledons are not considered as an important part of the plant body, especially after the establishment of the new plant and the appearance of the first pair of photosynthetically active leaves, their resistance to radiation is interesting and probably has to do with the fact that tissue construction and arrangement are already set, within each cotyledon, since embryogenesis. Therefore, besides the increased number of hair on the cotyledons of the exposed plants, it seems rather normal that no other changes can be observed at the structural level.

A notably retarded plant growth after exposure to Radiofrequency radiation has been reported in Vigna radiata, Lens culinaris and Arabidopsis thaliana (Sharma et al., 2009; Akbal et al., 2012; Stefi et al., 2016). In the present study, cotton plants of the control
group were far more productive, in both experiments. The differences in biomass production were calculated to have been raised at 68% for the above ground part and by 44% for the root for the control plants of the first experiment, compared to their exposed counterparts, and 65% for the above ground part and 55% for the roots for the second experiment, respectively.

Leaves of the control plants are much thicker (1st exp = 58% thicker, 2nd exp = 33% thicker), less compact and possess larger epidermal cells. More chloroplasts can be observed in the mesophyll cells, a fact justifying the higher terminal biomass and higher photosynthetic pigments quantity. Such differences have already been reported for the model-plant Arabidopsis thaliana in a similar experiment (Stefi et al., 2016). More multicellular, capitulate trichomes are present on both the upper and the lower epidermis of the exposed leaves. The secretive trichomes observed were far fewer than those presented by Wise et al. (2000), in their SE micrographs, although they did not figure out any numbers. Yet, raised trichome number is compatible with those of plants grown under more stressing environmental conditions (Christodoulakis, 1989; Fahn and Cutler, 1992; Kjær et al., 2012). No multicellular branched trichomes were observed on either epidermal tissues (adaxial – abaxial) in both types of leaves, in both experiments.

It has been documented that plants subjected to stress exhibit a reduction in the number of their chloroplasts and their pigment content (Zhang et al., 2016; Stefi et al., 2016). This probably has to do with the stressing conditions imposed by the 1800 MHz radiation which in other systems induces ROS levels increase (Manta et al., 2014). They also present a less elaborated or severely disturbed fretwork in their chloroplasts (Psaras and Christodoulakis, 1987; Christodoulakis and Fasseas, 1990) and an increased number and size of plastoglobuli, a feature considered to be one of the early indications of an environmental stress (Wellburn et al., 1972; Psaras and Christodoulakis, 1987; Christodoulakis and Fasseas, 1990; Lianopoulou et al., 2015; Shao et al., 2016). Our observations on mesophyll cells, with TEM, revealed that chloroplasts, from the
cells of the exposed leaves, actually appear with serious destruction. Their lamellae do not seem to exist any more while no signs of organized membranes in the form of grana can be observed. This is a tremendous problem since proteins and pigments functioning in the photochemical events of photosynthesis are accommodated in the thylakoid membranes (Taiz and Zeiger, 2010) while various components of the photosynthetic apparatus are located in different areas of the grana and the stroma lamellae (Dobrikova et al., 2013). The ATP synthases of the chloroplast are located on the thylakoid membranes (McCarty, 2005; Speeta and Schoefs, 2010) while stroma, which contains what may be Earth’s most abundant protein, rubisco (Taiz and Zeiger, 2010), seems extremely electron dense and seriously disturbed.

Wreckage of chloroplasts and the strong reduction of their pigment content — which is in agreement with current literature — means that exposed leaves can not be but less productive, so that the total yield (biomass) of the exposed plants appears inferior.

Concerning the roots, our data indicate that they are readily affected, producing less biomass (Table 2). This is in agreement with other investigations (Sheridan et al., 2010). It has also been reported that roots are affected by microwave (915 MHz) radiation in concern to the induction of a significant increase of micronuclei after exposure, ranging from a 2.3-fold increase above the sham value, at the lowest specific absorbance rate (SAR) level and up to a 7-fold increase at the highest SAR (Gustavino et al., 2015). Yet, no data is available for the tissue structure and arrangement as well as for the structure of the root cells. Our observations revealed a massive response for the cortex cells adjacent to the innermost cortex boundary, which is the endodermis. The accumulation of secondary metabolites, which are phenolics by nature, has long ago been reported for endodermal cells of the roots of Quercus coccifera (Christodoulakis and Psaras, 1988). It is unusual for the cells of an underground organ to accumulate phenolics but, these multi — role metabolites seem to appear whenever stressing conditions are present in the environment (Christodoulakis, 1992) yet the study of the phenolic — antioxidant response has been considered as a challenge in the field of comprehending the radiation induced stress and evaluate possible enhancements in the production of various phytochemicals (Alothaman et al., 2009). Moreover, exposed roots possess larger pericycle cells, a feature that can not be evaluated. Response to mobile phone radiation was also reported for the nodules developed both in Pisum sativum and Trigonella foenum-graecum. They seem to increase with the increase of the exposure (Sharma and Parihar, 2014).

Finally, an interesting point has to do with the results obtained from plant exposure to RFR under different growth conditions. Although the optimal temperature band ranges from 20 °C to 30 °C, it seems that the higher temperature is somehow protective to RFR induced damages.

5. Conclusion

The effect of the non-ionizing radiation at the microwave band, on the Gossypium hirsutum young plants, after a long term exposure, can be considered as significant. The disastrous effect on chloroplast structure, the reduction of the photosynthetic pigments and the suppression of the photosynthetic potential, are the main causes for the significant reduction of the primary productivity. Moreover, a serious effect on the underground part of the plant was recorded but this cannot be evaluated yet.

Acknowledgements

Gratitude to Spirova Agricultural Co for providing the cotton seeds.

References


