Effects of Gamma Radiation on Crop Production

Hafsa Ali, Zoya Ghori, Sandal Sheikh, and Alvina Gul

Abstract The increasing world population has raised concerns over food security. In order to feed the world, the projected target is to double food production by 2050. However, this objective has been interrupted by many global challenges, including climatic change and a reduced ozone layer. The Earth is protected by layers of atmosphere. The stratospheric ozone protects living organisms from harmful radiation. Plants use sunlight for photosynthesis and as a consequence face harmful radiation. Depletion of stratospheric ozone has increased radiation entering the surface of the Earth. Radiation is divided into two types: ionizing radiation, where gamma rays are most prominent; and nonionizing radiation, including UV rays. UV rays (high energetic radiation) cause heritable mutations in the genome of plants that exacerbate plant physiology, environmental factors, plant growth, and affect photosystem and soil properties which ultimately affect crop productivity, leading to the incidence and progress of crop diseases. However, plants have evolved methods to reverse the genetic changes by UV radiation by delaying growth and cell division that helps in DNA repair. There have been further studies on plant responses, including in DNA repair enzymes, endogenous photodamaging molecules, and repair machinery towards UV radiations in crop plants. Gamma radiation is high-frequency rays consisting of high-energy protons that penetrate the cell and cause ionization. Ionization of plant cells causes disruption of the normal processes of the cell ultimately affecting crop yield. Gamma rays are dose dependent, where a low dose has fewer side effects in contrast to a high dose that affects plant phenotype, including various cell organelles and biochemical components. However, there are several biochemical parameters to identify the damage caused by this radiation. Nevertheless, the plant defense mechanism is activated under a low dose of gamma rays to cope with the damage. Gamma rays also have various benefits in all applied fields and are used to create crop mutants. This chapter discusses the effects of radiation, predominantly UV and gamma rays in crops and their benefits.

Keywords Gamma radiation • Crop production • Antioxidant defense system UV rays

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1 Introduction

One of the major global issues is to feed the speedily increasing population of human beings. With the rapidly growing rate of population, the expected rate by 2050 will be 9 billion; therefore, there is a need to increase food production (The Royal Society 2009; Hakeem et al. 2012; Wargent and Jordan 2013). However, due to climate change we are not able to mitigate our food requirement (Godfray et al. 2010; Wargent and Jordan 2013). Earth is surrounded by a layer of gases called atmosphere. It shelters life on Earth by maintaining its temperature and protects life on Earth from the harmful radiation of the sun. The atmosphere has five layers: troposphere, stratosphere, mesosphere, thermosphere, and exosphere (http://eo.ucar.edu/basics/wx_1_b.html). The troposphere starts from the Earth and extends 7 miles above. It is the nearest layer of the Earth. We breathe in this layer and this layer has most of the atmosphere gases. The mesosphere is present 30 miles above the Earth; it is the coldest part of the atmosphere. The temperature of this region is 13 °F (Flannery 2006). The thermosphere is present above the mesosphere; this layer is present 50 miles above the Earth and the temperature of this region is 360°F. The exosphere is the outermost layer of the Earth and extends into space. In this layer satellites revolve around the Earth (Kubesh et al. 2008). The stratosphere separates the lower layer from the upper layers of the mesosphere and thermosphere. Its altitude spreads from 10 to15 km, containing most of the ozone's atmosphere (Campillo et al. 2012). Ozone is divided into two types: ground ozone and ozone layer.

Most of the harmful radiation is absorbed by the ozone layer in order to protect the living organisms that live on Earth. Ozone started accumulating in the atmosphere as a waste gas about 200 billion years ago, and when photosynthetic organisms started releasing oxygen (McMichael 1993) 400 Ma ago evolution occurred and aquatic plants moved to the land to begin terrestrial life. Life on Earth is protected from harmful radiations and sustained by the ozone layer (McMichael et al. 2011). Solar radiations are of different types and range from infrared to ultraviolet. Not all types of radiation reach Earth. Radiations that have shorter wavelengths (UV) are absorbed by the stratospheric ozone (Campillo et al. 2012). Unfortunately, depletion of ozone and climatic change are occurring due to anthropogenic activity (McMichael et al. 2011), resulting in environmental deviations. The industrial revolution has polluted the environment (Kakani et al. 2003a, b, c).

In the late twentieth century industrial chemicals such as chlorofluorocarbon which is used in refrigerator and propellant sprays and their intermediates, hydrochlorofluorocarbon, destroy the stratosphere layer (Minorsky 2004). Chlorofluorocarbon has the largest capacity to destroy the ozone layer. They have a half-life of 50–150 years. According to the US Environmental Protection Agency 1 chlorine molecule can destroy 0.10 million ozone molecules. These chemicals react with ozone to produce free radicals that destroy the ozone (McMichael et al. 2011). It is estimated that six types of hydrochlorofluorocarbon (HCFC) and seven types of chlorofluorocarbon (CFC) compounds have a role in ozone depletion. Although the use of chlorofluorocarbon compounds has been reduced, the ozone layer is reaching its maximum depletion. These radiations have affected not only human lives but also lives of plants and all other living organisms on the earth. Crops are badly affected by these solar radiations (Minorsky 2004).

All living organisms present on Earth are constantly exposed to radiations. Radiations travel in the form of energy from the source. The two main sources of radiations include natural radiations and man-made radiations. Natural radiations include natural resources with sun and lightning as the major causes. However, man-made radiations are the result of anthropogenic activity such as: rays as by-products of industrial activities, radiations from medical and scientific applications, wireless communication, and so on (Ng 2003). Radiations that radiate from the sun are of various wavelengths; most of them are invisible to the human eye. Short wavelength radiations are considered harmful and energetic (http://earthobservatory.nasa.gov/Features/UVB/uvb_radiation.php). Electromagnetic radiations are emitted from the sun, and range from infrared to ultraviolet radiations. Not all types of radiations reach the Earth's surface that only absorbs the radiations having shorter wavelengths. The ozone layer mostly absorbs the radiations and stops these radiations from reaching Earth. Different layers of the atmosphere act as filters for the radiations. These layers of the atmosphere absorb different parts of the radiation and reflect them either to the Earth or back into space (Campillo et al. 2012).

2 Types of Radiations

2.1 *Ionizing Radiations*

These radiations have wavelengths less than 100 nm (Ng 2003). These radiations are charged high-energy particles such as high-energy photons and electrons. Ionizing radiations are of two types including: gamma radiations and X-rays. Gamma rays are categorized in ionizing radiation because these radiations produce free radicals in the cell when they interact with atoms or molecules. These free radicals damage the cell, but sometimes modify the cells and components. Damage or modification of the cells and components depends upon the level of radiation. These radiations cause changes in the physiology, morphology, anatomy, and biochemistry of the plants (Kim et al. 2004; Kovacs and Keresztes 2002; Wi et al. 2005; Hamideldin and Hussin 2014). The effect of these radiations is dose dependent, as these rays stimulate growth in plants at low dose (Al-Safadi and Simon 1990). Therefore, these radiations are important in modifying the plant genome for crop improvement. It is estimated through studies that overall mutants created from radiation are 2570 and among them gamma rays have produced 1023 crop mutants (Hamideldin and Hussin 2014). X-rays are electromagnetic radiations, ionizing radiations, a photon of energy that resembles gamma rays. Gamma radiation and alpha radiation are emitted from different parts of atoms, but have the same properties. X-rays are radiated from outside the nucleus, whereas gamma rays are emitted from the nucleus (Radiation: Facts, Risks and Realities 2012).

2.2 Nonionizing Radiations

Nonionizing radiations include radiation with wavelengths greater than 100 nm. Nonionizing radiations are further divided into electromagnetic fields and optical radiations. The optical radiations include visible light, UV radiation, and infrared radiations (Ng 2003). Visible light ranges from 360 nm to 760 nm. This visible light has the largest effect on the life of living organisms (Campillo et al. 2012). Plants use visible light in photosynthesis and change carbon dioxide into organic molecules such as glucose, starch, sucrose, and so on. These organic molecules are used in respiration to produce energy (Kovacs and Keresztes 2002). Visible light is important for photosynthesis, but the radiations ranging from 400 to 500 and 600 to 700 are most essential. Radiations between 500 and 600 nm are assisted by accessory pigments as they have low ability to be absorbed in pure chlorophyll (Campillo et al. 2012). Infrared radiation has wavelength ranges from 760 nm to 4000 nm (Campillo et al. 2012). These radiations have small quantum because of their longer wavelength. The biological effects of these radiations depend upon the absorption of the energy. These rays penetrate 20 mm into the tissues (Kovacs and Keresztes 2002).

UV radiations have shorter wave length ranges from 200 nm to 400 nm. These types of radiations are absorbed by ozone, which is present in the stratosphere (Campillo et al. 2012). Generally, these rays are not categorized in ionizing radiation because these radiations only ionize some types of molecules under certain conditions. The absorption and emission of ultraviolet radiation involve larger quanta than the visible light. The ultraviolet photon has much energy to carry out a photochemical reaction by breaking down the chemical bonds (Kovacs and Keresztes 2002). Ultraviolet radiation is found in the category of nonionizing radiations and it is found in 8 % to 9 % of total radiation emitted from the sun. Plants need sunlight for the process of photosynthesis; sunlight comprises ultraviolet radiations. Therefore, plants are directly exposed to the ultraviolet radiations. Plants—being living organisms—respond to UV radiations. UV rays also damage plant processes such as physiological processes and DNA damage (Stapleton 1992).

UV radiation is divided into three types: UV-A, UV-B, and UV-C. UV-A radiations are the less harmful part of ultraviolet radiations. This ray ranges from 320 to 400 nm and has a relatively higher wavelength than UV-A and UV-B; it comprises 6.3 % of solar radiation. The ozone, which is present in the stratosphere, absorbs ultraviolet radiations that have shorter wavelengths, so the depletion of ozone has no effect. The ozone layer is more effective as it absorbs UV radiation shorter than 280 nm; this absorption effectively decreases with an increase in wavelength greater than 280 nm, and at 320 nm it reaches approximately zero (Robberecht 1989). UV-B rays are more harmful than UV-A, but less harmful than UV-C. However, they cause severe damage in plants. The wavelength of UV-B radiation ranges from 280 nm to 20 nm. This radiation comprises about 1.5 % of the total solar radiations. Even a minor decrease in the level of ozone has a large effect on the level of UV radiation (Madronich 1992, 1993). One percent decreases in the ozone increase the

UV-B level, which reaches to the biosphere. UV-C radiation has a shorter wavelength ranging from 200 nm to 280 nm. Among UV radiations, UV-C is the most harmful radiation for living organisms.

3 Effect of UV Radiations on Crop Plants

Ultraviolet radiations (UV) are known to cause significant damages to crop plants and the overall ecosystem. Even small changes in its level can cause devastating effects on life on Earth. There are basically two types of damages inflicted by UV radiations, damage to DNA, which leads towards mutations, and damage to plant physiological and biochemical functions. These damages can either be inflicted directly on the particular process or on the regulatory molecules involved in that process. Examples of such damage include membrane disruptions, protein conformational change, effect on plant hormones and pigments that ultimately affects the plant growth, yield, development, and numerous cellular processes such as photosynthesis and respiration (Zlatev et al. 2012). The damage inflicted by UV significantly depends on the quality and quantity of photosynthetic active radiation (PAR) which is actually the amount of solar radiation required by plants to activate photosynthesis. The balance of UV and PAR is necessary for the protection of plants because the ration of PAR that reaches the Earth remains the same and it is not absorbed by ozone whereas it is the opposite for UV. It has been confirmed that high levels of PAR compensate for the negative effects of UV and serve as an acclimatization factor. Hence, in recent studies PAR is always taken into account while analyzing the effects of UV on crop plants (Gotz et al. 2010).

Many studies have been reported on the effects of UV radiations. Among them UV-B are more common because UV-B levels directly depend on the ozone layer and those levels are continuously increasing due to ozone depletion. The effect of UV-B can be categorized as the effect on morphological, physiological, and biochemical processes and DNA damage and changes in genotype of crops.

3.1 *Effect of UV-B on Crop Morphology*

UV-B radiations are known to cause many anatomical and morphogenic changes in crop plants, including smaller leaf size, folding, discoloration and browning (Teramura et al. 1984), reduced hypocotyls, and increased thickness of leaves (Adamse and Britz 1996) that lead to plant stunting. These effects are elevated when PAR levels are reduced (Teramura 1983). Further alterations in height, stem diameter, length of internodes, leaf area, stomatal number and length, as well as changes in floral morphology have also been observed. Figure 1 shows the effect of UV-B on leaf morphology. These morphogenic changes are also protective mechanisms of crop plants that prevent them from high levels of UV-B (Jansen et al. 1998).

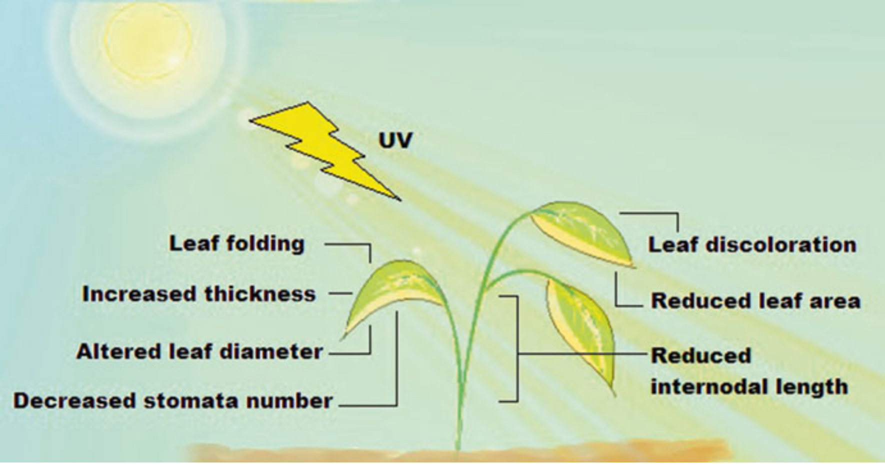

Fig. 1 The effect of UV-B on leaf morphology of crop plants

The introductions of such changes in plants due to the effect of solar radiations are known as photomorphogenic responses. These responses can change the architecture of plants due to the presence of photoreceptors including phytochromes, UV-B photosensory system, and photoreceptors for UV-A/blue light (Briggs and Olney 2001). Different assays have been designed to check the levels of gene expression that are either stimulated or inhibited by these responses (reviewed in Jansen 2002).

Early studies on crop plants show changes in height, leaf blade, and leaf area that have been observed in rice (Barnes et al. 1993). Similar alterations in pea plants with respect to plant height (Vu et al. 1984) and leaf area that resulted in decreased cell division (Mepsted et al. 1996) have been observed as well. Reductions in stomatal number and surface area, and vegetative morphological changes including increase in waxy layer, leaf epidermis (Tevini and Steinmuller 1987), and leaf optical properties (Cen and Bornman 1993) have been studied. Gonzalez et al. (1996) also studied the decrease in the waxy layer due to high-level exposure to UV-B.

Recent studies on crops such as soybean cultivars Jindou and Heidou revealed Heidou to be more sensitive to UV-B radiations and showed morphological changes including smaller and thicker leaf and hairy lamina (Feng et al. 2003). Changes in plant height and stem diameter have been observed due to UV-B radiations. In a study on Tartary buckwheat, decrease in plant heights was observed in eight populations and an increase was observed in four populations. Similar results regarding reductions in stem diameter were also visible in seven populations (Yao et al. 2007). Wheat studies regarding exposure to UV-B also showed morphological changes such as changes in the height of crops, tiller numbers, and alterations in leaf area. When wheat was exposed to the solar spectrum, about 20–24 % increase in height was observed, which corresponded with the increase in the number of nodes and length of internodes. About 50 % increase in leaf area and 114 % increase in the number of tillers was observed (Kataria and Guruprasad 2012b). In a similar study done on southern US rice cultivars, 5–12 % reduction in plant height, 7–10 % increase in length of culm, and a considerable increase in total leaves and leaf area was observed. However, no change in the number of tillers was seen due to high exposure to UV-B (Mohammed and Tarpley 2011).

Research has been conducted to check the effects of UV and PAR on the morphology of barley. In this case, UV/PAR treatment was applied to the crop and effects were calculated after 7 days. When UV + PAR+ treatment was done, reduction in leaf length of young leaves and in leaf area was observed. Under UV + PAR- treatment significant reductions in leaf area and width were observed along with an increase in leaf thickness. In UV + PAR+ and UV-PAR+ treatments decrease in leaf area was studied. This proves the importance of PAR in decreasing the adverse effects of UV-B radiations (Klem et al. 2012). In another study done on leaf anatomy and morphology, the appearance of necrotic patches on leaves visible after 4–5 days exposure to UV-B in cotton was observed but no changes in crop development were seen. A 47 % decrease in plant height, severe reduction of internodes, branch lengths, and leaf area along with a significant increase in the number and lengths of stomata and thickness of waxy layer were observed while studying leaf ultrastructure. Studies on structural morphology showed thinner leaves due to reduced mesophyll cells and increase in air spaces (Kakani et al. 2003b). Mung bean cultivars HUM 1 and HUM 12 also showed cupping and folding of leaves and the development of light purple necrotic patches due to elevated UV-B levels (Choudhary and Agrawal 2014a). Choudhary and Agrawal (2014b) also demonstrated morphological changes due to UV-B in another study on pea cultivars such as decrease in leaf area, root nodules, and root-to-shoot ratio in field conditions.

Floral morphology of crop plants is also observed to change due to UV-B exposure. This in turn affects reproduction of the crop plants which ultimately affects yield. In the same study done by Kakani et al. (2003a), cotton showed a decrease in flower size due to a decrease in the size of the petals, and the number of anthers was also reduced. Floral morphology studies have also been done on soybean which showed decreased petal length and length of staminal column. The flower size was reduced about 31–38 % and flower length about 28 % under different levels of UV. Pollen morphology is also affected by an increase in the UV-B exposure causing shriveled appearance, lack of apertures, and other structural effects (Koti et al. 2005). Hence UV-B has a significant consequence on the morphology of crop plants that can affect their growth and ultimately reduce their yield.

3.2 Effect of UV-B on Crop Physiological and Biochemical Processes

The major effect of UV-B exposure to crop plants results in malfunctioning of the crops' physiological and biochemical functions such as photosynthesis. This can in turn affect the plant's pigment concentration, crop phenology, reproductive processes, biomass and grain quality, and increase environmental stresses including abiotic and biotic factors. UV-B can also affect the metabolite concentration, amino acids, proteins, and total sugar content, and can cause changes in nitrogen levels.

3.2.1 Biomass and Grain Quality

The morphology of plants guarantees their particular biomass. As UV-B affects the morphology of crop plants, it also alters the biomass, the grain quality, and grain number and ultimately affects the yield. It has also been studied that reduction in photosynthesis can also decrease the biomass of crops. There are many crops on which studies of biomass have been conducted. Research on cotton shows that increased exposure to UV-B reduces the biomass of crops (Gao et al. 2003). In a study conducted on soybean cultivars a significant decrease in biomass and dry weight was observed due to the changed morphology of all organs of the plant (Feng et al. 2003). In another study on 20 soybean cultivars altered biomass and grain yield has been observed due to UV-B sensitivity of crop plants (Yanqun et al. 2003).

In rice there is a variation among the varieties on the effect of the UV-B. Some are more tolerant than others such as in different southern US rice cultivars and that's why biomass production varies in them (Teramura et al. 1991). However, in a recent study on rice, a dry weight decrease of 23 % was observed for aboveground parts. Alterations in grain weight were also seen that significantly decreased the yield in ranges from 13 % to 79 % in different cultivars as compared to plants grown under a UV-B free environment (Mohammed and Tarpley 2011). The reason for the decrease in plant dry matter is basically due to a decrease in the rate of photosynthesis and stomatal conductance, which are explained further in Sect. 1.2.2.2. A research conducted on maize revealed decreases in grain yield when exposed to UV-B for different time periods. The maize yield was less affected when exposed to UV-B for a short-term period of 1 week as compared to maize plants that were exposed to UV-B for 4 weeks. In contrast the grain quality was enhanced due to increase in grain protein content (Yin and Wang 2012).

UV-B also affects the biomass in Tartary buckwheat. It is calculated to be decreased in six populations and the difference between the control plants and affected plants ranged from 3 to 5.2 times. An increase in biomass in some populations and their yield enhancement has also been observed. The thousand grain weight calculation of the same plants showed a decrease in six populations whereas specific leaf area was increased (Yao et al. 2007). Another study by Yao et al. (2006) also showed reduced thousand grain weight, seed yield, and biomass in both spring and autumn varieties of Tartary buckwheat. Research conducted on red and green lettuce revealed reduction in growth and biomass due to high UV-radiation. The plants showed higher weights of 47 % when placed under UV blocking film and their vegetative growth significantly increased as compared to when the same plants were placed under transparent film. Among the lettuce types, red lettuce showed lower dry weight as compared to green lettuce. The rate of growth and dry weight also depends on the period at which plants were transferred from under UV-blocking to UV-transparent film (Tsormpatsidis et al. 2010).

The grain quality of wheat has also been under consideration. Although the positive effects of UV-B enhancing grain quality have been studied in 10 wheat cultivars (Zu et al. 2004) and rice (Hidema et al. 2005), negative effects have also been reported in maize (Gao et al. 2004). But recent studies have shown that biomass and grain quality and grain yield of wheat largely depend on the crop phenology and developmental stages, that is, at what period the plant was exposed to UV-B radiation (Calderini et al. 2008). However, in a study done in 2009, wheat varieties under increased UV-B radiations did not show any change in crop phenology as compared to control plants. In contrast to these results, the aboveground biomass, particularly leaf blade biomass and grain yield were negatively affected by UV-B and a decrease of 11–19 % and 12–20 %, respectively was observed (Lizana et al. 2009). In another study on wheat by Feng et al. (2007) spring wheat growth, economic yield, and biomass were also reduced by high UV-B levels.

Reductions in biomass with alterations in plant organs were reported in sorghum varieties due to a decrease in the process of photosynthesis. Similarly the grain number, grains per panicle, and length of panicle showed increased growth when exposed to solar radiation free of UV-B (Kataria and Guruprasad 2012a). Another study done by Kataria and Guruprasad (2012b) on wheat varieties showed significant increase in aboveground biomass and grain yield. In a study on mung bean cultivars HUM 1 and HUM 12, grain and yield reductions of 8.5 and 10.6 %, respectively, were observed (Choudhary and Agrawal 2014a). Similarly 29 and 19 % reduction in biomass and seed yield of pea cultivars HUP-2 and HUDP-15, respectively, were observed in field conditions which also showed that UV-B can have a considerable effect on crop quality and economic yield (Choudhary and Agrawal 2014b). Hence UV-B has negative effects on plants, plant biomass, and agronomic traits such as growth and yield.

3.2.2 Photosynthesis and Photosynthetic Pigments

UV-B has a major impact on the rate of photosynthesis and its pigments. As mentioned in the above sections UV-B stressed crops undergo many physiological and morphological changes which inhibit photosynthesis that in turn alter the crop biomass and subsequently affect the crop's yield. The decrease in the photosynthesis process occurs due to the damage on the molecular mechanisms of the process or due to the decrease in photosynthetic pigments such as chlorophyll and carotenoid content. Biochemical changes include alterations in leaf RuBisCO level (Ziska and Teramura 1992) and binding proteins of Photosystem II along with alterations in physiological factors such as stomatal number, rate of transpiration, and water-use efficiency that are also negatively affected by UV-B. The stomatal conductance and the opening and closing of the aperture are known to associate with environmental factors such as light and humidity, and on plant hormones such as abscisic acid. Thus a stressful environment with increased UV-B can affect the stomata's function

(Jansen and Van Den Noort 2000; Teramura 1983). Thylakoids and grana in the chloroplast are also affected as UV-B can break their membranes and rupture them completely (He et al. 1994; Kakani et al. 2003a).

UV-B radiation at low PAR levels has also greatly affected the process of photosynthesis. The process is inhibited by the inactivation of photosystem II that normally occurs in the thylakoid membranes of chloroplasts. Photosystem II is a part of the electron transport chain that functions to generate ATP required for plant functions. Inhibition of this system will inhibit the synthesis of ATP and affect the photosynthetic activity. The photosystem II reactions are mediated by D1 and D2 proteins. They are very sensitive and degrade due to high UV-B levels, which can be another factor for the decrease in photosynthesis rate. UV-B is also known to affect RuBisCO (Ribuose-1, 5-biphosphate carboxylase oxygenase) during the Calvin cycle for fixing CO_2 into sugar molecules. The reduced synthesis of sugars is due to limited triose-P usage, which resulted in decreased RuBP regeneration and hence CO_2 fixation capacity of the plant decreases (reviewed in Kakani et al. 2003b and Zlatev et al. 2012). Figure 2 shows the effect of UV-B on photosystem II and Calvin cycle.

Numerous studies have been reported to check the activity of photosynthesis in the presence of excessive UV-B in crop plants. In a study on wheat by Lizana et al. (2009), a considerable decrease in chlorophyll content was observed. Chlorophyll a

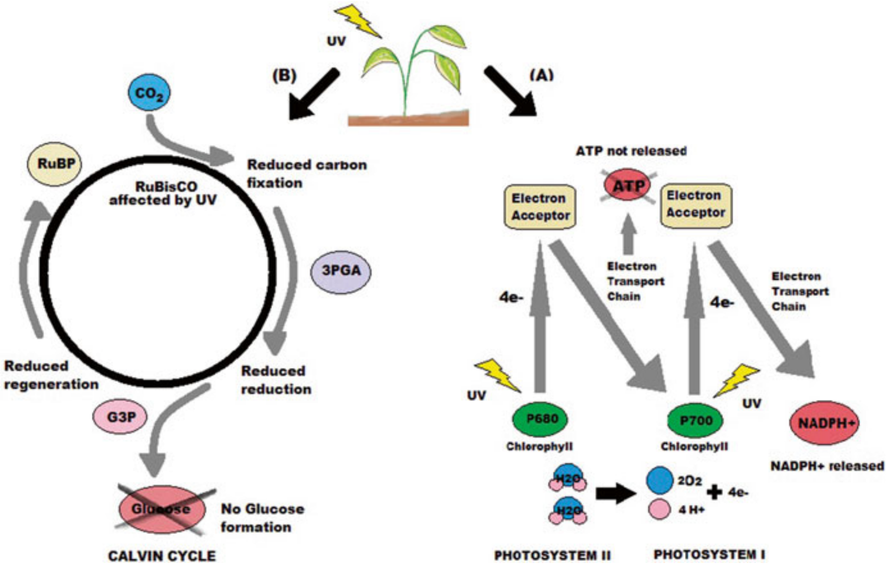

Fig. 2 The effect of UV-B on the process of photosynthesis. (**a**) Photosystem II affected by UV-B stress at the end of which ATP is not released. However, photosystem I is not affected by UV-B and NADPH+ is released at the end of the process. (**b**) Calvin cycle affected by UV-B in which RuBisCO is affected. This in turn reduced the carbon fixation, reduced reduction from 3PGA to G3P which leads to reduced regeneration of RuBP

was found to be more sensitive than chlorophyll b but a considerable decrease in a/b ratio was observed by increased UV-B exposure. Similar results were seen when carotenoid concentration was measured. The reason for the decrease in pigments was due to the lack of compounds or antioxidant enzymes that have the capacity to absorb UV-B radiations and hence affect the thylakoids, photosystem II, and yield of the wheat crop. Similarly chlorophyll a and b, ratio a/b, as well as carotenoids were found to be higher when sorghum varieties were exposed to solar radiation in exclusion of UV-B. Because chlorophyll a content was found to be greater than chlorophyll b, the a/b ratio was decreased. This resulted in an increase in photosynthesis rate and in turn increased the biomass and growth of crop plants (Kataria and Guruprasad 2012a). Similar results regarding the negative effects of UV-B on photosynthetic pigments have been seen in wheat (Feng et al. 2007). A moderate reduction of carotenoids such as neoxanthin, xanthophylls, and luten and in chlorophyll a and b were also seen in cucumber varieties whereas a significant decrease in all the pigments was observed in soybean (Yao et al. 2006).

During the process of photosynthesis II, naturally occurring isotopes of carbon are used that are ^{12}C and ^{13}C. ^{12}C is more commonly incorporated by plants than ^{13}C during the assimilation process. But there are several studies which report that an isotope δ^{13}C is also used and its uptake by the plant during carbon fixation is affected by UV-B and found to be decreased which further lowers the rate of photosynthesis (Naidu et al. 1993). Some studies have reported no significant change in δ^{13}C due to UV-B exposure (Kim et al. 1996). However, in 2003 it was studied that δ^{13}C composition in plants decreased due to UV-B exposure, which resulted in the decrease in the rate of photosynthesis and stomatal conductance. Consequently, it affected the photosynthetic pigments such as chlorophyll and carotenoid content. Inasmuch as there was no change in the concentration of δ^{13}C in the environment, the UV-B stress was the only factor that affected its uptake by plants (Feng et al. 2003). Studies on spring wheat exposed to UV-B have also shown a reduction in carbon stable isotope δ^{13}C composition along with decreased water-use efficiency and in stomatal conductance that consequently affected the photosynthesis rate (Zhao et al. 2009).

Photosynthetic pigment concentrations were also found to be negatively affected by UV-B in Tartary buckwheat. Total chlorophyll content and carotenoids were decreased mostly in young leaves. The populations with higher levels of pigment content were found to be more affected by excessive UV-B (Yao et al. 2007). Another study on Tartary buckwheat showed a decrease in photosynthetic pigments in high UV-B as compared to ambient UV-B and spring buckwheat was much more affected than autumn buckwheat (Yao et al. 2006). Elevated UV-B has also led to a decrease in chlorophyll and pigment concentrations in both HUM and HUM 12 cultivars of mung bean, which was due to disruption of the chloroplast structure (Choudhary and Agrawal 2014a, b). Another study on the grapevine plant showed the negative effects of UV-B exposure in the short- and long-term period in which leaf chlorophyll levels and carotenoid concentrations were severely reduced. However β-carotene levels were significantly increased due to high UV-B level (Martinez-Luscher et al. 2013).

Various studies on rice cultivars have been done to identify the decline in photosynthesis rate due to high UV-B irradiance. In research done in 2010, the photosynthesis rate was observed to be reduced by the decline in CO_2 assimilation in all cultivars under study. This was also found to be due to the reduction of RuBisCO as well as a significant reduction in photosystem II and the electron transport chain. However, no changes in photosystem I were calculated (Fedina et al. 2010). In another study on nine cultivars of rice, UV-B exposure resulted in decreased rates of photosynthesis and chlorophyll a and b at the grain filling period but the leaf carotenoid levels did not show any difference. The decrease in photosynthesis was more visible in inbred cultivars in comparison to hybrids (Mohammed and Tarpley 2011). In the leaves of *Oryza sativa* (rice), the rate of photosynthesis was also found to decline due to UV-B exposure in the leaves because of reduced stomatal conductance and gaseous exchange. The leaf fluorescence when calculated to check chlorophyll levels was recorded to be majorly affected. Chlorophyll a was more strongly affected in leaves than chlorophyll b which decreased the chlorophyll a/b ratio. Among the pigments, xanthophylls pigments were less severely affected and carotenes showed minor deviations from normal levels. However, the leaves of crop plants formed after the exposure showed no significant effect. This confirmed the insensitivity of rice leaves to excessive UV-B (Lidon and Ramalho 2011).

In two varieties of barley, the effects of PAR and UV-B have been studied on chlorophyll levels and stomatal conductance. When the UV + PAR-condition was applied, chlorophyll content was reduced, photosystem II was targeted, and a decrease in photosynthetic enzyme activity, RuBisCO content, and stomatal conductance were observed. However, in PAR+ condition, chlorophyll a and b were not affected (Klem et al. 2012). In a similar study on lettuce, plants grown under UV transparent film showed no difference as compared to those grown under UV blocking film. However, when they were transferred from UV blocking to UV transparent film, the plants' stress condition decreased due to the change in environment. In the second experiment, no significant differences were measured when the stomatal conductance and rate of photosynthesis were measured. This showed that ambient UV treatment was not able to affect red and green lettuce cultivars (Tsormpatsidis et al. 2010).

It was also studied that the photosynthetic capability of the plant is affected by nitrogen concentration inasmuch as nitrogen is associated with photosynthetic enzymes, membrane proteins, and chlorophyll and carotenoid composition (Field and Mooney 1986). In a study on maize reported in 2005, UV-B affected the photosynthetic rate and stomatal conductance. Activities of enzymes, pigments, RuBisCO concentration, as well as chlorophyll a and b were severely affected. However, the nitrogen levels when measured were also found to be reduced. This in turn affected photosystem II as the pool size of electron acceptors decreased. Thus, the study proved that the rate of photosynthesis is dependent on the plant's nutrition and correlates with nitrogen levels (Correia et al. 2005).

When the plants are exposed to high levels of UV-B, they become stressful and release signaling molecules that are required for plant defense. One such molecule is jasmonic acid (JA) that is released due to biotic and abiotic stresses (Dar et al. 2015).

In this study on wheat the effect of UV-B was observed in the presence and absence of JA. Results showed that photosynthetic pigments and chlorophyll florescence were minimized when UV-B was exposed to the plant in the presence of JA. This also proposed that photosystem II which was affected by UV-B exposure was remedied by the application of JA. Therefore JA is involved in increasing the tolerance of plants exposed to high UV-B (Liu et al. 2012). Hence UV-B can affect the photosynthetic activity of crops and can reduce them significantly under high irradiance. Various photosynthetic processes and pigments are altered and if not controlled by UV-B exposure can lead to severe yield loss and poor crop quality.

3.2.3 Flavonoid Levels

Plants under stress conditions initiate many mechanisms to protect themselves from impairment. One such mechanism is the alteration of flavonoid levels, which are normally synthesized with the help of chalcone synthase (CHS) enzyme (Batschauer et al. 1991). When the plant is exposed to stress, changes in physiological and biochemical functions and DNA damage cause many pigments to release. In the case of UV stress, the photo repair is mediated by an enzyme called photoreactivating enzyme (PRE) which undergoes this mechanism by monomerizing cyclobutane pyrimidine dimer (CPD) known to cause DNA damage if not degraded. The formation of CPD initiates the flavonoid biosynthesis pathway and PRE activity which damages the CPD thus limiting its function. It is also known that PRE acclimatizes flavonoid biosynthesis due to UV-B irradiation stress (reviewed in Sancar 1994). Flavonoids also serve as the reactive oxygen species (ROS) scavenging secondary metabolites that protect the plant against oxidative stresses (Frohnmeyer and Staiger 2003) and are secondary to antioxidant enzymes to regulate the ROS level inside the plant under stress (Agati and Tattini 2010; Fini et al. 2011). There are many types of flavonoids that are present in plants. Table 1 shows some flavonoids and their functions.

Basically, there are two mechanisms by which these secondary metabolites protect the plant. Firstly by reducing free radicals such as O_2, H_2O_2, and $OH^{\cdot}$ or by chelating them with metals, thus stopping their formation and secondly by inhibiting ROS synthesizing enzymes and increasing UV-B absorption capacity (Pietta 2000). Because they reside inside the vacuole, the vacuole has a major role in ROS homeostasis and in regulating the activity of various oxidants (Mittler et al. 2004). Apart from flavonoids and antioxidants, plants also release some phenolic compounds that are induced when the plant is irradiated with high UV-B. Hydroxycinnamic acid (HCA) is a phenolic compound involved in protecting the plant from UV-B. These compounds also function by absorbing UV-B at specific wavelengths, but allow PAR to transmit to initiate photosynthesis (Morales et al. 2010).

As the accumulation of flavonoids in plants decreases ROS generation, it has been observed that flavonoid synthesis is induced more in plants that are sensitive to stress as compared to those less sensitive. It means that sensitive plants will encounter more oxidative stress (Tattini et al. 2005). In severe conditions flavonoid

Table 1 Different types of flavonoids and their known functions (Winkel-Shirley 2002)

Types of flavonoids	Functions
Isoflavonoids (e.g., naringenin)	Helps in the formation of nodules and in defensive roles
Aurones	Role in pigmentation of leaves
Flavones (e.g., luteolin, tangeritin)	Helps in nodule formation and defense
Anthocyanins (e.g., cyanin, malvin)	Role in pigmentation that helps to attract pollinators and enhance seed dispersal
Deoxyanthocyanidins	Role in pigment production and defense
Flavonol glycosides (e.g., Quercetin, kaempferol, myricetin)	Involved in protection against UV-stress, in producing purple pigment, male fertility, and signaling
Proanthocyanidins	Role in pigmentation and defense

biosynthesis is increased and more flavonoid accumulation becomes inversely proportional to the presence of other antioxidative enzymes, meaning that when antioxidants deplete in the plant due to stress, flavonoid activity is induced, making up the secondary antioxidative system (reviewed in Agati et al. 2012).

Various studies on crops have been reported that specify the stimulation of flavonoids due to UV-B stress. In a study on *Brassica napus*, low PAR levels and high UV-B stress increased the flavonoid accumulation in the plant. When UV-A stress was studied, it was found that UV-A only induced a low level of flavonoids as compared to UV-B (Wilson et al. 2001). In a similar study on white asparagus, activities of antioxidant enzymes PAL (phenylalanine ammonia lyase) and POD (peroxidase) were checked under UV-B irradiation. PAL levels did not demonstrate any significant activity at high UV-B concentration, but at low UV-B high PAL was observed. In contrast, POD activity was elevated due to UV-B stress. Such differences were also seen in other parts of the plant. In apical meristems high POD levels were observed, and in the basal region PAL activity was high. The flavonoid level was also increased with an increase in quercetin activity (Eichholz et al. 2012). In a study on mustard cotyledons UV-B affected the flavonoid concentration and the levels of the PRE. The results indicated that radiations for a short period of time can induce anthocyanin production whereas flavonol biosynthesis occurred due to radiation exposure for a long time. PRE was found to be induced by far-red light and long-term exposure (Buchholz et al. 1995).

Research on *Ligustrum vulgare* plants also showed flavonoid accumulation due to high light stress. The plants when placed in sunlight exclusive of UV-B showed a severe decrease in oxidative enzymes that was also enhanced by salinity stress. The oxidative damage led to the initiation of synthesis of flavonoids that reduced the ROS accumulation (Agati et al. 2011). A study in 2012 in maize leaves indicated that nitric oxide (NO) colocalizes with flavonoids. It was found that flavonoids and NO were accumulated in the upper epidermis of leaves irradiated with UV-B as compared to leaves that were nonirradiated. It also indicated that both NO and flavonoids are systematically produced as a result of UV-B stress (Tossi et al. 2012).

Thus the above studies prove that flavonoids have a major role in photoprotection of plants and their mechanism is initiated by high levels of UV-B.

3.3 DNA Damage and Repair Mechanism

As mentioned before, UV-B can cause DNA damage in crop plants. Under stress conditions two adjacent pyrimidine bases form a pyrimidine dimer that affects the DNA replication and transcription processes. Photodamage by UV-B occurs by the construction of the cyclobutane pyrimidine dimer (CPD) and pyrimidine, pyrimidone 6-4 photoproducts (6-4 PPs) that are formed between two carbons of adjacent pyrimidines C_6 and C_4. UV-B exposure to crop plants can also alter the concentration of thymine dimers (TD) inside the leaf. It has been observed that high UV-B exposure increased TD levels and subsequently increased DNA damage, but the repair mechanism was too slow such that it could only repair low levels of TD and not the high concentration. TD levels were also found to be reduced under negative UV-B condition. Hence it has been proved that DNA damage is stimulated at high UV-B (Schmitz-Hoerner and Weissenbock 2003).

Plants have evolved many repair mechanisms to counter the damage induced by UV stress. There are basically two mechanisms by which photorepair can occur in plants. Firstly, by the accumulation of flavonoids that are UV-absorbing compounds, and phenolic compounds in the epidermis of leaves so that mesophyll cells can be protected and the photosynthesis process is not affected (Kolb et al. 2001), and secondly, by excision of pyrimidine dimers (CPD or 6-4 PPs). Photolyases are the enzymes that initiate photorepair mechanisms and can remove the defected pyrimidine dimers (Britt 1996). These dimer formations result in the accumulation of antioxidants as mentioned in Sect. 1.2.2.3. It has also been studied that pyrimidine dimers can cause cell death by interfering with the DNA replication and transcription process if not removed and if somehow they bypass the repair mechanism, they are translated and lead to the development of mutations. There are many mechanisms for the repair of DNA damage. Among them two are most common, photoreactivation (PR) and nucleotide excision repair (NER; Tuteja et al. 2001). The first DNA repair pathway is a light-dependent photoreactivation repair mechanism or the PR pathway in which CPD or 6-4 PPs dimer formation occurs. Photolyases that undergo the repair mechanism are of two types, CPD photolyase and 6-4 photolyase. These photolyases carry flavin cofactor FAD which acts as an electron donor and breaks the CPD or 6-4 PPs dimer in the presence of light (Britt 2004). Figure 3 shows the photoreactivation pathway for pyrimidine dimer repair.

The second method for repairing DNA is nucleotide excision repair. It is an evolutionary conserved mechanism in which DNA damage induced by radiations and other environmental factors is repaired. Figure 4 shows the NER mechanism for the repair of DNA damage. NER has two mechanisms by which UV-induced DNA damage can be repaired. First is the NER-global genome repair (NER-GGR) which is able to repair damage to DNA in the entire genome that is untranscribed.

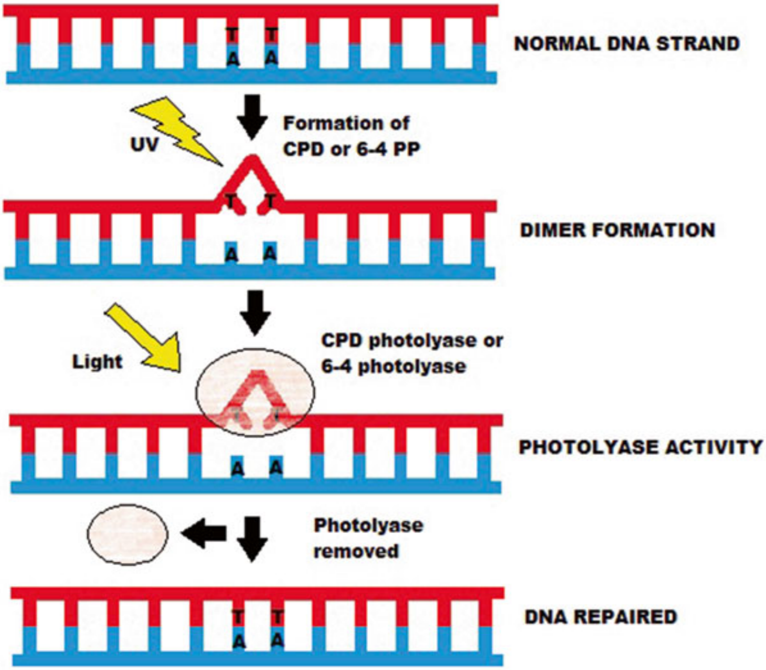

Fig. 3 Photoreactivation (PR) pathway for the repair of pyrimidine dimers mediated by photolyases (explanation from text)

Second is the NER-transcription coupled repair (NER-TCR) which can only repair DNA damage in transcribed strands but does not interfere with the transcription process. In the NER-GGP, the damage is recognized by the UV-damage binding protein (UV-DDB) and a complex of *xeroderma pigmentosum* complementation group C (XPC) and RAD23. However, in a review by Tuteja et al. (2009), NER-GGP recognizes UV-B induced damage to DNA by XPC/hHR23B. Contrastingly, in the NER-TCR pathway, damage recognition is mediated by Cockayne syndrome A and B (CSA and CSB) which are in turn activated when RNA polymerase reaches the site of damage.

After recognition both NER-GGP and NER-TCR unwound the DNA helix by a transcription elongation factor-IIH that includes other subunits such as *xeroderma pigmentosum* complementation group B (XPB), *xeroderma pigmentosum* complementation group D (XPD), and *xeroderma pigmentosum* complementation group A (XPA). After unwinding excision proteins, namely *xeroderma pigmentosum* complementation group F/excision repair cross-complementation (XPF/ERCC1) and *xeroderma pigmentosum* complementation group G (XPG) excise the 20–30 base oligonucleotides on the damaged strand. The undamaged strand is held intact by replication protein A (RPA). RPA prevents the excision of the complementary undamaged strand and enables it to be used as a template for the repair synthesis of the damaged strand. The last step of NER is the gap filling stage in which proliferating

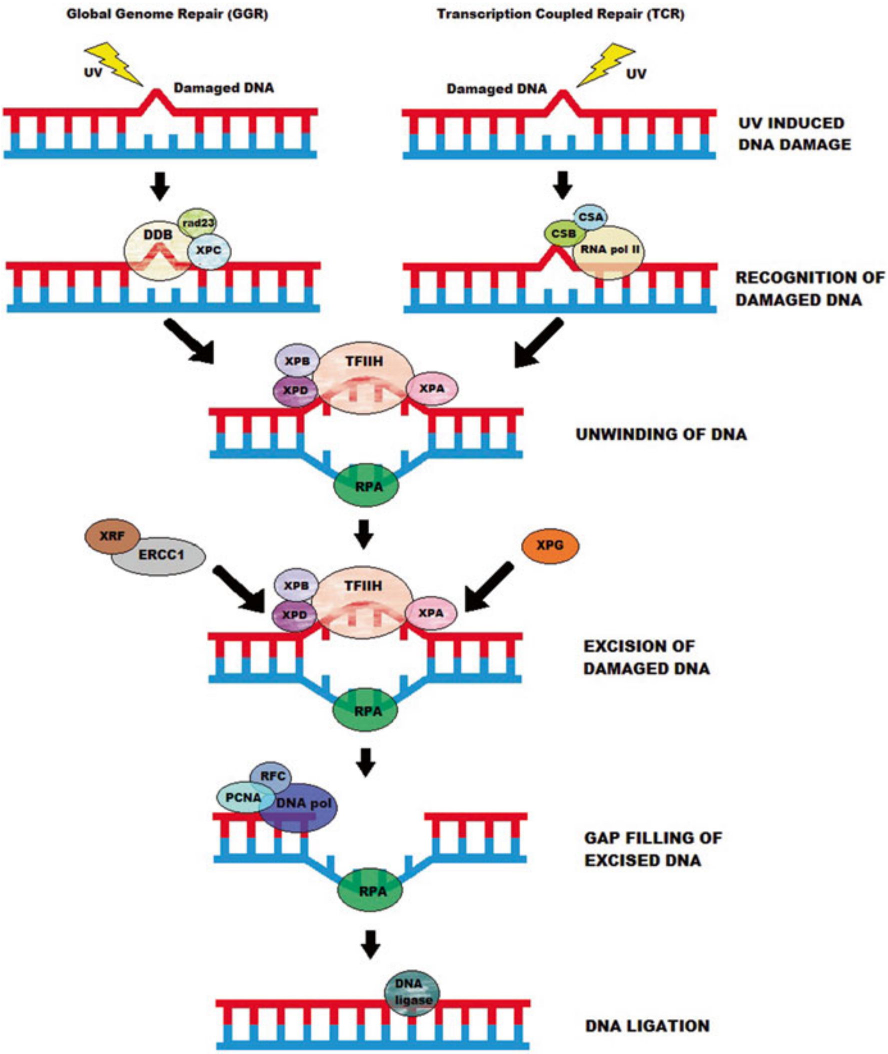

Fig. 4 NER mechanism for the repair of DNA damage induced by UV-B (explanation from text)

cell nuclear antigen (PCNA) and replication factor C (RFC) carry out repair synthesis of excised strands mediated by DNA polymerase subunits δ and ϵ. The strands are then ligated by DNA ligase I (Britt 2004; Kimura and Sakaguchi 2006; Tuteja et al. 2009; Balestrazzi et al. 2011).

Different studies have been reported in plants, particularly *Arabidopsis*, which explains how UV-B can cause DNA damage. A study shows that temperature and environmental factors can affect the photorepair mechanisms and can increase DNA damage. It was found that CPD and 6-4 PPs formation were not affected by normal temperature and direct UV-B stress and their concentrations remained normal.

However, the photorepair mechanism, particularly of 6-4 PPs was reduced under high temperature and UV-B exposure as compared to CPD concentration which was measured to be minutely decreased. This shows that repair mechanisms of a plant are directly dependent on temperature (Li et al. 2002). CPD activity has also been observed in spinach due to UV-B exposure. Expression of the photolyase gene was found to be higher in leaves and flowers as compared to roots in both male and female plants (Yoshihara et al. 2005). In research on *Arabidopsis*, mammalian Cockayne syndrome As (CSA) orthologue ATCSA- 1, involved in NER-TCR was discovered. It was found to be working simultaneously with DNA binding protein 2 (DBP2). It was studied that in normal conditions the ATCSA-1 expression was stronger than DDB2 but under UV-stress, DDB2 expression was increased and ATCSA-1 expression remained constant. Hence this showed the importance of both ATCSA-1 and DDB2 in the NER-TCR mechanism (Biedermann and Hellmann 2010).

In *Arabidopsis*, UV-B has been shown to affect the expression of DNA that regulates the cell cycle. Under UV-B stress, the expression of marker genes revealed that UV-B downregulated the histone H4, E2Fa genes and the transcript CYCD3; 1 which mediate the G1-S transition whereas a gene transcript KPP2 that normally reduces the G1-S transition showed increased expression. The transition from the G1-S phase is also shown to be affected by CPD formation and not by ROS. In another study on *Arabidopsis* and maize, DNA damage has been found to be repaired by the mismatch repair system (MMR) which is involved in recognition of mismatched or unmatched bases. In this study MSH2 and MSH6 genes were found to be contributing to the DNA damage and also affected cell cycle regulation and their expression was found to be upregulated. However, MSH2 and MSH6 mutants when compared to wild-type also showed more accumulation of CPD which confirmed that they are involved in response pathway to DNA damage (Lario et al. 2011).

4 Introduction to Gamma Radiation

There is a constant exposure of radiation that all the living organisms face every day, including cosmic radiation and natural radiations occurring from rocks and soils, radionuclides. Moreover, anthropogenic activities are the main cause of producing absorbed radiations through radioactive waste storage, nuclear radiation accidents, and nuclear power production (Vanhoudt et al. 2014; Daly and Thompson 1975). Electromagnetic radiations are of various types such as gamma rays, X-rays, visible light, and UV rays (Wi et al. 2005). These radiations have different frequencies and energies. Among all radiations gamma rays are considered to be the most energetic form of radiation with an energy level starting from 10 KeV to several 100 KeV. This quality makes them more penetrable than alpha and beta rays (Kovacs and Keresztes 2002). Gamma radiation (electromagnetic radiation with high frequency) is an important ionizing ray, as it comprises high-energy photons. High penetration properties of photons cause ionization of matter and plants by indirect interaction

(Vandenhove et al. 2010. Previous studies show that these rays cause modification in growth and development, cause DNA damage, and interrupt the metabolic pathway (Esnault et al. 2010; Kovalchuk et al. 2007; Vandenhove et al. 2010) consequently causing deleterious effects on the plant. Nevertheless, useful reports have also been published on growth stimulation by the effect of a low dose of gamma rays (Marcu et al. 2013; Miller and Miller 1987).

Plants, sessile organisms, constantly face fluctuations in environmental conditions, for instance, different harmful radiations of sunlight, air pollutants, and other abiotic stresses. Any changes in the somatic cells are represented as mutations in gametes, as plants lack reserved germline and meiotic cells are produced in late development (Walbot and Evans 2003). Gamma rays are ionizing rays that react with atoms and molecules present inside the cells to produce free radicals. Production of free radicals depends on the irradiation level that causes damage or modification of components in plants, ultimately affecting morphology, physiology, anatomy, and biochemistry of plants. As a result, physiology and metabolism are affected such as altered photosynthesis, expansion of thylakoid membrane, accumulation of phenolic compounds, and variation of the antioxidative system (Kim et al. 2004; Kovacs and Keresztes 2002; Wi et al. 2005).

4.1 Effects of Gamma Radiations on Plants

4.1.1 Effects on Phenotype of Plants

Chaudhuri (2002) found that a high dose of gamma rays reduces root and shoot length. Kiong et al. (2008) reported that the rate of seed germination depends on the level of chromosomal damage caused by increasing doses of radiation. It was determined that radiations reduce growth regulators such as cytokines by breaking them down or not synthesizing, thereby increasing plant sensitivity. Kim et al. (2004) determined that the low dose of gamma rays ranging 1–2 Gy when exposed on *Arabidopsis* seedlings slightly enhanced their growth, in comparison to seedlings exposed to high radiations of 50 Gy. He hypothesized that a low level of gamma rays helps the plant to overcome daily stresses during growth conditions, including variations in light intensity and temperature. Low levels of gamma rays induce growth stimulation signals by increasing the antioxidative ability of cells or by changing the hormonal signaling in plants (See Fig. 5). Gamma ray treatment in the early stages of seed germination triggers the activation of RNA or protein synthesis (Abdel-Hady et al. 2008). Toker et al.'s (2005) findings show that radiations up to 200 Gy increase shoot length, but further increase to 400 Gy causes despair in shoot length. Melki and Marouani's (2010) research also concluded that a low dose of 20 Gy gamma radiations enhances the root length and number by 18–32 %. Rashid and Daran's (2013) findings showed that increasing duration of gamma rays decreases the average germination rate in ginger (44 %), which was not as severe as that of the maximum exposure period of 150 s. Gamma rays decrease the growth rate with an increase in radiation dose due to mutations in DNA that synthesize DNA at the interphase leading to plant bud disruption and resulting interruption of cell differentiation. They estimated that increasing doses are injurious to the plant cell and ultimately interfere with the growth of plants. However, Konzak (1984) described that doses reducing 25 % of seedling height are considered useful rays

A high dose of gamma radiations is not only injurious to the ultrastructural organelles, but also affects the phenotype of the plant. Wi et al. (2007) determined that treating pumpkin plant with a high dose of gamma radiations (1 kGY) can cause an imbalance of plant growth regulators and result in curling and yellowing of leaves. Pumpkin tissues were found sensitive to gamma radiations (Micron 38 (2007). A high dose of gamma irradiations (100, 200, 300, and 400 Gy) decreases the germination process in seeds, but does not affect already germinated wheat seed (see Fig. 5). Borzouei et al. (2010) demonstrated that germination capacity decreases with increase in irradiation. Melki and Marouani (2010) also verified that irradiated and nonirradiated wheat seed showed no significant differences at low dose. Borzouei et al. (2010) stated a low dose of 100 Gy showed no central changes in root weight; nevertheless a high dose up to 200–300 incredibly lowered the root weight compared to controls. Melki and Salami's (2008) findings were contradictory to Borzouei et al.'s (2010) results that a radiation range of 15 Gy causes improvements in chickpea dry weight in contrast to 0 Gy doses of gamma rays.

Majeed and Muhammad (2010) reported that a high dose of 70–80 kGy delays initiation and completion of germination in *L. sativum,* as a result of inhibitory effect of rays on seed dormancy (Fig. 5). Such high radiations are injurious to seeds

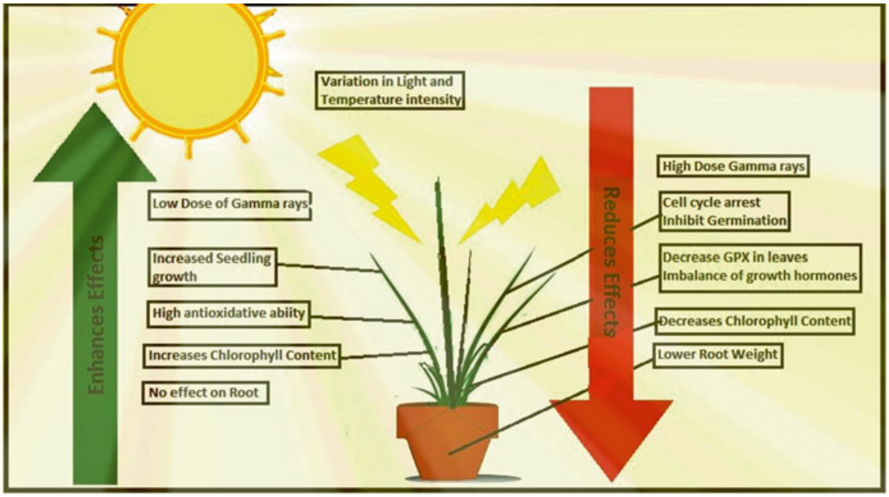

Fig. 5 Comparison of high dose and low dose of gamma radiations effects: high dose of gamma radiations that effects phenotype, ultrastructural organelles, causing cell arrest of the plant, whereas low dose of gamma rays enhances seedling growth and helps cell fight back daily stresses in its growth. It also increases the antioxidative ability of cells (Wi et al. 2007; Melki and Marouani 2010)

and have the ability to cause inhibitory effects on seeds of angiosperms and gymnosperms (Thapa 1990). However, germination can also increase as a result of the stimulating effects of RNA or protein synthesis (Kuzin et al. 1976) or due to eradication of the bacterial population along with spores and other fungi (Gruner et al. 1992). Borzouei et al. (2013) reported that gamma rays above 200 Gy in Roshan wheat prevent seed germination. Marcu et al. (2013) also investigated the role of different gamma radiation doses in causing morphological abnormalities in maize. He described that rays from 0.1 to 1 kGy affect maize germination up to 11–62 %, shoot length of maize is decreased to 9–62 %, and the root length is reduced from 9 to 71 %. Radiation ranging from 0.5, 0.7, and 1 kGy inhibited maize seed germination, however, 0.1, 0.2, 0.3 kGy lessens the content of photosynthetic pigment. Vanhoudt et al. (2014) presented that different doses of gamma rays caused changes in root and leaf weight but growth was not inhibited. These changes were the result of biological changes taking place in plants, instead of effects of radiations. A chronic dose (a low dose for a long time) affects *A. thaliana* more than an acute dose, a high dose for short time. Kurimoto et al. (2010) demonstrated that older plants are more tolerant towards these radiations as they are fully equipped with internal structure and biomass when irradiated. However, immature plants are not completely established which makes them sensitive to radiation stress.

4.1.2 Effects on Ultracellular Organelles

Wi et al. (2005) reported that gamma rays ranging from 1, 5, and 50 Gy cause certain changes in the ultrastructure of the *Arabidopsis* stem when observed under TEM. The cortical cells of the stem were highly vacuolated forming a thin separation between cell wall and vacuoles. The cytoplasm containing various organelles was reported to comprise high-density electrons. Nevertheless, the cytoplasm and chromatin material were well dispersed and well persevered in all the irradiated plants. At 50 Gy range plasmalemma gets separated from the cell wall. In short, low irradiations do not affect the morphology of the plant cell organelles, in contrast to high irradiations that cause prominent changes in the organelles, especially chloroplasts. Kovacs and Keresztes (2002) described that gamma rays interact with the atoms of water and produce radicals; these radicals have the ability to damage plant physiology, morphology, anatomy, and biochemistry (Ashraf et al. 2003).

Kim et al. (2000) determined the symptoms caused by different doses (high and low) of gamma irradiation involved in enhancement or inhibition of germination, seedling growth, and various biological responses (Wi et al. 2005). Preussa and Britta (2003) stated that a high dose of gamma radiations contributes in cell cycle arrest during G_2/M phase, inhibiting growth during cell division. Radiation causes damages to cell organelles that can be observed with the help of a microscope. Fenech (2000) defined that radiation induces damages which can be observed in micronuclei, nuclear material that arises from chromosomal fragments or when the chromosome is not present in the nuclear membrane. Micronuclei were first investigated in China rice seeds when bombarded with gamma radiations, and other ions including Ar and Fe ions of different doses. Exposure of different radiations with the pollen cells showed that micronuclei are most sensitive to the radiations (Mei et al. 1994). Takatsuji et al. (2010) demonstrated the effects of gamma rays on onion seedlings where a low dose increased the amount of micronuclei. However, a high dose of gamma radiations decreased the amount of micronuclei.

Wi et al. (2007) determined the damage caused by gamma rays at the ultrastructural level. The result provided knowledge about how the ionizing radiation affects the cellular mechanism of plants. At 1–5 Gy irradiation the chloroplast present in stems was well arranged; however, when the irradiations were amplified to 50 Gy, chloroplast in the cortical cells of the stems were altered with swollen and destructed thylakoids, but with the same size as that of chloroplast exposed to low irradiated gamma rays. Some of the changes affect the cellular structure of plants such as thylakoid membrane, which reduces photosynthesis ability that further causes accumulation of phenolic compounds (Kovacs and Keresztes 2002; Kim et al. 2004). Kim et al. (2004) designated that gamma rays after 50 Gy cause ultrastructural changes in the irradiated plant cell, which shows that chloroplasts are sensitive to gamma rays as compared to other organelles present in the plant cell. Plastids were also found to be affected as senescence was inhibited and due to differentiation into the agranal stage (Kim et al. 2004). Wi et al. (2005) demonstrated that the chloroplast structure was intact under a low dose of gamma rays (1–5 Gy) displaying well-organized thylakoid and membrane. However, the chloroplast structure at high gamma radiation displayed altered cortical cells of stems with swollen and destructed thylakoid membrane.

Gamma rays cause dose-dependent changes in plants by inducing production of harmful free radicals in cells (Kovacs and Keresztes 2002) that further damage the nucleic acid, proteins, and lipids present in the membrane (Bolwell and Wojtaszek 1997), which results in reduction of membrane integrity (Lee et al. 1998). Affecting the plant cell on a cellular level leaves a wide impact in minimizing the plant development that reduces the yield (Ogawa and Iwabuchi 2001). A high dose of radiations also increases numerous plastoglobuli in the chloroplast by increasing their size in the stroma of the cell. Wi et al. (2005) also reported the deposition of starch grain in the chloroplast at a high dose of gamma rays, but a low dose of radiation-treated cells was similar to controls. The damage and disorientation of thylakoids and grana influence carbohydrate transport by inhibiting it (Carmi and Shomer 1979; Bondada and Oosterhuis 2003). Chloroplasts are more sensitive to high doses of gamma radiations, as numerous plastoglobuli on chloroplast are produced as a result in stems, along with accumulation of starch grains (Wi et al. 2007) indicated that the accumulation of starch in the chloroplast along with damaged grana and thylakoid affect the carbohydrate transport. Other radiations and environmental factors also cause a similar disruption (Molas 2002; Quaggiotti et al. 2004).

The size of both the chloroplasts irradiated with high and low doses of gamma rays remained the same. Similarly, the cristae of mitochondria were also well organized under a low dose of gamma rays, and the high dose of gamma rays (50 Gy) caused distortion in mitochondria and distended the endoplasmic reticulum membrane (Wi et al. 2005). Mitochondria remained well-organized, but slightly enlarged when exposed to a low gamma dose; although a high dose increases the endoplasmic reticulum and distorts the mitochondrial shape, its size is not changed (Wi et al. 2007).

A high dose of gamma rays on seeds also causes certain morphological disruptions in protein synthesis, hormone balance, leaf gas exchange, water exchange, and enzyme activity. Irradiated seed also shows defective chloroplast which decreases the chlorophyll a and b ratio; such leaves show white stripes on affected areas (Abe et al. 2002; Palamine et al. 2005; Mei et al. 1994, 1998). Ionizing radiation affects the plants by producing free radicals that cause oxidation of atoms and results in plant cell damage (Zaka et al. 2002). Reactive oxygen species have basal expression inside the plant cell, but in a very low amount, however, the induction of the radiation increases the amount of ROS to maintain cell homeostasis (Polle 2001). These result in reduction of the photosynthetic electron transport chain as reductants of Calvin cycles are reduced. This condition leads to photo-oxidation by the increase of electron flux to O_2 that produces superoxide, H_2O_2 and hydroxyl radicals (Foyer and Mullineaux 1994). These high reactive species are responsible for creating damage to the photosynthetic apparatus; Agarwal et al. (2008) also reported that *Cyanobacterium anacystisnidulans* irradiated with ionizing radiations have high levels of ROS.

4.2 Effect of Gamma Irradiation on Biochemical Parameters

Gamma radiations result in the production of a reactive oxygen species that induces oxidative stress, and ultimately affects structural and functional molecules of a plant by causing a disturbance in normal metabolic pathways (Al-Rumaih and Al-Rumaih 2008; Ashraf 2009; Noreen and Ashraf 2009). Radiation causes radiolysis of water present inside the cell resulting in the production of reactive oxygen species such as hydrogen peroxide (H_2O_2), superoxide anion, hydroxyl radicals (OH), and singlet oxygen [O] (Kovacs and Keresztes 2002; Luckey 1980; Miller and Miller 1987; Quintiliani 1986). When a gamma ray acts on a crop it disturbs various morphological features of plant that are easily visible, but to countercheck the effect of various gamma ray doses on plants different biophysical parameters are adapted to measure the disastrous effects. The prominent measurable parameters are the content of chlorophyll, proline, and starch.

4.2.1 Chlorophyll Content

Gamma radiations affect many biophysical contents of the plant, where photosynthesis is widely studied. Radiations also affect the wide range of autotrophic organisms (Angelini et al. 2000; Esposito et al. 2006; Rea et al. 2008) including plants (Mei et al. 1994; Palamine et al. 2005). Gamma rays are responsible for causing different alterations in physiology and biochemical properties of plants at various doses, and disturb hormonal balance, enzymatic activity, and leaf exchange at a high level (Kiong et al. 2008). Photosynthesis begins with the absorption of light energy by plants in order to manufacture their own food. Different components of photosynthesis altogether such as pigment protein complexes which play a role in absorbing the light, enzymes reduced for the carbon reduction cycle, and electron transport carriers. This photosynthetic complex responsible for performing various activities is altered by the radiations. Ionizing radiations decrease the capabilities of the photosynthetic apparatus by damaging the photosystem (Angelini et al. 2000). Under high light intensities the plant's photosynthetic antenna complexes play an important role in combating variable intensities. These complexes allow photosynthesis by capturing light energy, protect photo-oxidative damage of chlorophyll from ROS, and release excess energy as heat (Niyogi 1999).

Borzouei et al. (2013) determined the high dose of gamma rays on cv-Roshan and Bam varieties of wheat. Where the chlorophyll content in cv-Roshan was increased after exposing it with radiations of 100 Gy and more, the chlorophyll content was decreased in Bam cultivar from 12.8, 26 and 29 %. Gamma radiations also damaged the photosynthetic pigments that reduced photosynthetic capabilities of plants (Kiong et al. 2008). A high dose of gamma rays up to 500 Gy decreases chlorophyll content by 80.91 % and decreases the organized pattern of grana and stroma thylakoid (Alikamanoglu et al. 2011). The intensity of chloroplast damage caused by the ionizing radiations depends on the plant growth stage, species, and the intensity of the dose. Holst and Nagel (1997) supported that woody species are less sensitive to acute radiations as compared to herbaceous plants that easily get damaged by radiation exposure, where a lethal dose to *Arabidopsis thaliana* that causes severe damage is 150 Gy (Kurimoto et al. 2010). The banana fruit thylakoid membrane is dilated on exposure above 0.2 kGy and further results in loss of grana stacks (Strydom et al. 1991).

Kovacs and Keresztes (2002) demonstrated that a high dose of gamma rays has an adverse effect on chlorophyll synthesis of wheat. Kim et al. (2005) demonstrated that carotenoid pigments immediately recover from the irradiation as they are highly radiosensitive. Found that red pepper irradiated with 16 Gy significantly increases the chlorophyll content. Additionally, Khodary et al. (2003a, b, c) confirmed these results that radiation of 20 Gy on dry seeds improves total chlorophyll content, which increases chlorophyll activity and increases the amount of soluble sugar. A comparative study was done on the chlorophyll content in treated and control *Paulownia tomentosa* seedlings when exposed to radiations along with controls. The chlorophyll content was increased with an increase in the radiation until it reached 100 Gy. Furthermore, an increase in radiation had no effect on the chlorophyll a, b levels, but the amount decreased to 81.36 % at 400 Gy, and 500 Gy gamma ray exposure caused an 80.91 % reduction (Alikamanoglu et al. 2007). Borzouei et al. (2013) demonstrated that the chlorophyll content rises in two cultivars of wheat by increasing the gamma radiations after 100 Gy. However, radiation reaching 200 Gy prevents wheat Roshan cultivar germination in soil, and comprises minimum chlorophyll. Borzouei et al. (2013) noted that chlorophyll a contents are higher than chlorophyll b, as a result of the high radiation dose above 100 Gy which depresses the chlorophyll content level in wheat cultivars.

The chlorophyll level is increased when exposed to low levels of radiation as a result of an activated enzyme system (Ferreira-Castro et al. 2007). Zeerak et al. (1994); Osama (2002) reported high chlorophyll content in plants including tomato (*Lycopersicon esculentum L.*), maize (*Zea mays L.*), rice (*Oryza sativa L.*), and wheat (*Triticum aestivum L.*) along with improved yield when exposed to variable radiations. However, Soehendi et al. (2007) described that gamma rays affect leaf canopy and seed yield of mung bean; especially those having a larger area of leaf are highly exposed to photosynthesis which results in greater yield rate. According to Rashed et al. (1994) gamma rays change the protein pattern in the protein band. described an increasing gamma rays dose that affects the pigments on leaves of *Holcuslanatus L.* Gamma radiations harm the pigment for photosynthesis as a result of damaged thylakoid and chloroplast and cause disorganization in the pattern of grana and thylakoid (Kiong et al. 2008; Borzouei et al. 2010; Marwood and Greenberg 1996).Borzouei et al. (2010) described that 100–200 Gy of radiations increases the level of chlorophyll a, b up to 64.5 % in wheat seedlings. Radiation at 100 Gy showed an increase in level of chlorophyll a as compared to b. However, a high-level 300 Gy decreases the total chlorophyll a and b content. A low level of chlorophyll indicates selective destruction or degradation of chlorophyll b precursors (Kiong et al. 2008). Kim et al. (2004) have evaluated that 16 Gy radiation in red pepper plant stimulates growth, and changes in photosynthesis can be the cause (Wi et al. 2007). Vanhoudt et al. (2014) determined the effects of gamma rays on chlorophyll, specifically on photosystem II (PSII). He reported that the capacity of PSII remains constant when different dose rates of gamma radiation were applied on *A. thaliana*, in contrast to cadmium stress which decreases photosystem II capacity (Dias et al. 2013). Vanhoudt et al. (2014) reported that carotenoids protect the photosystem II by deactivating triplet chlorophyll and neutralizing the effect of singlet oxygen. Therefore, measuring the level of chlorophyll content after treating them with gamma rays helps to evaluate the impact of radiation in crops.

4.2.2 Effects on Biochemical Content

Radiations are responsible for breaking the bond between chains, cross-linking DNA molecules and protein molecules. Seedling growth contributes to the nutrition of the plant which comprises proteins, carbohydrates, and vitamins (Marin-Huachaca et al. 2002). Different levels of gamma radiations pose different effects on morphology, and biochemical characteristics such as producing amino acids (proline), stimulating seedling growth, and promoting germination. Amino acid contents are indicators to determine the effects of gamma rays on the crop plant. Amino acids are essential for human diets and the essential ones are required to be taken in the form of food to fulfill the requirement of normal growth. In amino acids, amino group (–NH2) is radiation sensitive (Siddhuraju et al. 2002). Satter et al. (1990) irradiated a low dose (0.10 kGy) of gamma rays and determined the level of amino acids in soybean, where a low dose increases protein content by inhibiting protein synthesis assembly (Reuther 1969). Inoue et al. (1975) reported that amino acids are released in irradiated rice at a low dose of 0.10–0.40 kGy. Ananthaswamy et al. (1971) described amino acids inside cells are decreased in irradiated wheat where free amino acid due to a low dose of radiation depends on the sensitivity of the exposed plant. The results were contradictory by Siddhuraju et al. (2002), who described that particular amino acid content (phenylalanine leucine and arginine) was increased at low dose 0.5–5 kGy and many other amino acids were reduced by high dose (5 kGy) of gamma rays in wheat, maize, mung bean, and chickpea. However, described that comparing the cowpea amino acid content with its controls were found reduced in amount as a result of an increase in gamma radiation.

Proline is a hydrophilic solute that helps in water shortages by replacing water around nucleic acid, protein, and membrane, where proline and nonaqueous tails of protein surface interaction help in increasing protein stability (Irigoyen et al. 1992). Prolines are important solutes that act as osmoregulators by contributing in stress tolerance, protection, hydrophobicity, active oxygen scavenging, and maintaining cell pH (Kuznetsov and Shevyakova 2007). Proline functions to scavenge the hydroxyl radical and acts as a cytosolic osmoticum that helps in regulating and stabilizing various structure and functions such as DNA, protein, and membranes (Kishor et al. 2005). Proline is not the only component involved in stability; it along with other compounds is referred to as “compatible solutes” to maintain the osmolality of cells in various organisms (Yancey 2005). Therefore, the more high proline content is present in a cell, the more it is protected against various stresses. Al-Enezi and Al-Khayri (2012) described radiations on *Phoenix dactylifera* with X-rays result in high proline content that helps to overcome the stress by radiations. confirmed the increased content of proline by increasing radiations, where the highest concentration of proline was recorded by treating with 100–200 Gy in *T. arjuna*. Therefore high proline content guarantees it as a compatible solute.

Falahati et al. (2007) reported that radiations promote the amount of antioxidants; as a result extra proline is not required to face damages caused by oxidative reagents. But Borzouei et al. (2010) contradicted this research by his findings that a slight increase in proline content was observed when wheat seedlings were treated with gamma radiations. Borzouei et al.’s (2010) results showed that proline content of wheat seedlings irradiated up to 300 Gy were not significantly different from nonirradiated seedlings, although in wheat of different genotypes the proline level was raised; however, in wheat -cv. Roshan a high level of proline was observed at 100, 200, and 300 Gy. The result shows that Roshan wheat is sensitive to rays (Borzouei et al. 2010). Borzouei et al. (2013) determined that gamma rays of (500 Gy), high dose, increases the amount of proline to 16 %, whereas 100 Gy on wheat cultivars (Bam and Roshan) decreases proline to 9.3 and 23.6 %. Proline is involved in various functions such as preserving enzyme structure and activities; it reduces enzyme denaturation caused by environmental stresses including heat, NaCl, and the like (Ashraf and Foolad 2007; Kishor et al. 2005). Therefore, defining the amount of proline in the plant can be helpful in creating mutants.

Another biochemical parameter used to determine the effect of radiations is proteins. Seeds comprise all the important basic nutrients, where the seed of *Oryza sativa* comprises 14–20 % of protein, with 80 % of glutein as a total rice protein (Chrastil and Zarins 1994). Other protein components make up the rest of the 20 % including (1–5 %) of albumins with globulins about 4–15 % and 2–8 % of prolamins (Hulse 1989). Inoue et al. (1975) described that radiation inhibited protein synthesis which decreases the total amount of protein and carbohydrates at high dose in wheat and rice plant. Muskmelon (*Cucumismelo L.*) fruit retains the protein in its plasma membrane after 1 kGy of gamma rays (Lester and Whitaker 1996). This irradiation somehow activates the self-defense mechanism in plants (Marchenko et al. 1996). This mechanism works by increasing the production of certain enzymes as superoxide dismutase and compounds that contain sulfur (cysteine), which helps either to remove or neutralize the free radicals formed inside plants (Qui et al. 2000). Radiations also increase the amount of sucrose in potato tubers when treated with 3–4 kGy (Hayashi and Kawashima 1982).

Maity et al. (2009) observed the influence of gamma radiations on important proteins, where total protein content was affected by the radiations. This depletion was the result of a high dose (1 kGy) of gamma rays on *O. sativa.* However, when *C. arietinum* was irradiated with 1 kGy of gamma rays a 3 % reduction in soluble proteins was observed where 6 kGy showed the loss up to 27 % of proteins. Aziz and Mahrous (2004) described the effects on wheat and bean when a low dose of gamma rays was applied, where the protein content was not affected. Maity et al. (2004) compared the effects of gamma rays on protein contents *O. sativum* and *Cicer*, where the rice showed radiation resistant activity against the degradation of protein content. The amount of protein concentration helps to determine the lethal dose of radiation and its side effects on plant crops. Borzouei et al. (2013) demonstrated gamma radiation effects in the protein content of two wheat cultivars and they concluded that protein content increases after applying rays between 300 Gy and 400 Gy doses in the wheat–Bam cultivars, where, gamma rays of 200 Gy increased soluble protein content in Roshan cultivars and other Bam wheat cultivars comprised soluble protein content (38.91 ug/g Fw) were more than the nonirradiated wheat cultivars. Consequently, plants activate and keep on developing their defense system in response to gamma radiation (Qui et al. 2000; Jan et al. 2012). Al-Rumaih and Al-Rumaih (2008) concluded that the high content of proteins acts as a protective mechanism to fight the harmful effects of gamma radiation. However, inasmuch as an outcome of exposure to radiations causes radiolysis of water by radical oxygen, proteins are consequently fragmented and aggregate, forming cross-linking, and oxidation (Kiong et al. 2008; Afify et al. 2011). Although, Stajner et al. (2007) described that high doses up to 10 kGy slightly disturb the water component such as sugar, minerals, proteins, and the like Borzouei et al. (2013) explicitly described that reduction in protein content by exposure of 200 Gy is due to increase in proline and starch content for the defense and protection of protein against oxidation.

Described that treating with ionization radiations causes variation of concentration in the crop such as phenylalanine, valine, and glutamic acid. He described that after gamma radiation exposure most of the amino acids in millet pearl were stable except for leucine, glutamic acid, and phenylalanine, whose content was decreased from 32 to 23 mg/g on 5 kGy. This aromatic amino acid, phenylalanine, is dose-dependent and high rays of gamma radiation cause modification in this compound and lead to the formation of decarboxylation, hydroxylation (formation of amine in aqueous solution), or formation of complex compounds (Cataldo et al. 2011). The radiation induces the splitting of peptide bonds that form free radicals (Aziz et al. 2006). However, the protein content including proline, glutaminic acid, and valin was slightly decreased in millet flour at high radiation. According to Aziz et al. (2006) it is negligible and similar to nonirradiated flour. Many previous studies show that as the gamma radiations are increased the total amount of protein and carbohydrate content is decreased due to metabolic activities and hydrolyzing enzyme activities (Barros et al. 2002; Maity et al. 2004). Reported that gamma rays increase glucose absorption and decrease acetate and succinate absorption in carrot, and reduce all amino acids except serine and valine, whose amount was increased at 1 Gy. Reported the reduction of pectin and alginate viscosity. Demonstrated the degradation of oligosaccharides in legumes of Bengal gram (*Cicerarrietinum L.*) and cowpea (*Vignaunguiculata (L.) Walp*) between control and treated. Gamma rays are also considered to produce amino acids by breaking seed proteins (Maity et al. 2004; Kiong et al. 2008).

The original content of starch has low thermal resistance, low shear, and ability to retrogradation. Gamma rays are helpful tools in improving starch to enhance the physicochemical characters to starch in crops. Yu and Wang (2007) determined that gamma rays can be useful in cross-linking, grafting, and degradation techniques of polymer material. Gamma rays are responsible for breaking glycoside bonds that results in smaller fragments from the larger molecules. It is considered a useful technique due to its rapidity and effectiveness (Kang et al. 1999; Yu and Wang 2007). When gamma rays act on the starch they hydrolyze its chemical bonds and cause the formation of small polymers. The water binding capacity of starch along with high solubility and low viscosity is considered useful in food applications, and paper and textile materials (Kang et al. 1999). Akulova et al. (1970) investigated different effects of gamma rays in changing the properties of corn starch. Roushdi (1981) supported the previous findings that an increase in gamma ray dose decreases the starch content in corn up to 10 %.

Gamma rays break the glycosidic bonds apart into starch granules, which are further decomposed to produce macromolecules with small chains. This decreases crystalline content and distribution of amylose and amylose pectin in granules of corn (Ciesla et al. 1992). This modification changes the physical and chemical properties of native starch to improve its function that can be useful in food application (Hermansson and Svegmark 1996). Chemical modification in starch is common in food applications, however, physical modification of starch by radiation is widely accepted as it does not produce any by-products and is safe to consume (Bemiller 1997). Induction of gamma rays produces free radicals that cause fragmentation of starch and result in molecular changes (Grant et al. 1991), although increasing the radiation does not affect the moisture content of the starch with the increased dose of rays. Sokhey and Chinnaswamy (1993) reported that gamma rays of 20 kGy reduce the moisture to 28.3–23.07 % in lotus starch. This result is due to excess degradation of the amylose fraction that results in reduced amylose content by decreasing iodine binding (Sokhey and Chinnaswamy 1993). Abu et al. (2005) found that gamma radiations modify the starch content of cowpea and decrease swelling and pasting properties. Water absorption capacity, carboxyl content, and solubility are increased as a result of degradation of amylose (Gani et al. 2013).

4.3 Antioxidative Defense

Plants cells have a defensive, ROS regulating, system that consists of enzymes such as peroxidases (PX), catalase (CAT), superoxide dismutase (SOD), and ascorbate and glutathione; this system allows cell signaling while avoiding cellular damage (Mittler et al. 2004). Former studies show that under irradiation conditions, antioxidative defense systems regulate cellular stress responses (Kim et al. 2005; Vandenhove et al. 2010). Whenever a plant is exposed to gamma radiations superoxide dismutase (SOD) plays a defensive role in converting superoxide to hydrogen peroxide (McCord and Fridovich 1969). Additionally, catalase and peroxidases hunt for hydrogen peroxide produced during the reaction.

Halliwell (1974) specified that among all the reactive oxygen species H_2O_2 is always present in a standard amount inside the cell under normal growth conditions but whenever the amount of H_2O_2 is increased as a result of radiation it causes lethal effects inside the cell. Production of radicals causes disorder of the metabolism as the cellular structure in plants is disrupted due to induction of gamma rays and causes the following disturbances: expansion of thylakoid membrane, modulation of the antioxidative system, amount of phenolic compound increased variation in photosynthesis, and increase in phenolic compounds (Kim et al. 2004; Kovacs and Keresztes 2002; Wi et al. 2007). Gamma irradiation is highly effective and penetrating causing conformational changes, oxidation, formation of free radicals, and breaking of covalent bond with exposure to plant cells (Cheftel et al. 1985). Hydroxyl ions and superoxide anions produced as a result of radiations causes modification in lipids and proteins (Stajner et al. 2007). Changes in the molecular properties of proteins caused by gamma rays include oxygen radicals by radiolysis of water, fragmentation, and cross-linking of protein (Cho and Song 2000).

Changes in biochemical activities through production of various metabolites are quite prominent when a plant is exposed to gamma radiations. Cellular activity is disturbed due to production and accumulation of peroxides that cause oxidation of lipid membrane (Mead 1976). Ikeya et al. (1989) identified the physiological effects of gamma rays in plants. Voisine et al. (1991) described that free peroxidation of unsaturated fatty acid produces peroxyl radicals. Wi et al. (2006) described that pumpkin leaves and petioles showed high deposition of hydrogen peroxides when reacted by a high dose of 1 kGy. Middle lamella of parenchyma cells were the center of deposition, however, plasma membrane and vessels also deposit hydrogen peroxides. This accumulation is associated with high POD activity in the middle lamella of parenchyma cells (Wi et al. 2007).

Nevertheless, Zaka et al. (2002) determined that a protective cellular mechanism is present inside all organisms—plants, microorganisms, and animals—against the prominent effects of ROS produced by radiations. Calabrese and Baldwin (2003) reported that those plants are under constant influence of different radiations but they have the ability to cope with various stresses to a certain extent after which the ability decreases. Chakravarty and Sen (2001) proved that exposure to 140 Gy gamma ray decreases the glutathione–nonenzymatic antioxidants; consequently a low dose increases the activity of glutathione reductase. An oxidative mechanism helps the plant cell to avoid oxidative damage and to counteract the effects of ROS (Kiong et al. 2008). Plant cells cause certain alterations in gene expression to defend themselves that lead to defensive metabolic pathways. Synthesis of osmolytes is one of the most important protective mechanisms that requires proline synthesis and is essential for plant growth. Irradiated plants show a high level of proline involved in osmolyte synthesis. Alteration in proline content in environmental stresses and gamma radiation proved its involvement in protective mechanisms. (Esfandiari et al. 2008; Al-Rumaih and Al-Rumaih 2008).

Plants show protection against radiations by removing H_2O_2 and lipid hydrogen peroxides through the action of peroxidase, which shows higher efficiency of peroxidases than catalase. However, a low dose of gamma radiation activates and stimulates the peroxidase activity that helps the plant recover from initial degradation in chickpeas, and affect the peroxidase's isozymatic composition (Khanna and Maherchandani 1981; Shen et al. 2010). Peroxidase activity contributes in radiation and can help to understand radiation's role in plant growth inhibition, where damage due to irradiation causes different peroxidase isozyme patterns. Jain et al. (1990) described the effects of irradiation in the callus culture of *Daturainnoxia Mill* that had high peroxidase enzymatic activity. Later, Wada et al. (1998) also confirmed the isozyme activity of POD in *Nicotianadebneyi domin* and *Nicotianatabacum L. Nicotianadebneyi domin* with SOD activity and *Nicotianatabacum L.* with CAT activity as a result of gamma radiations. Vandenhove et al. (2009) reported that gamma rays enhance activity in (*Raphanussativus L.*) radish; CAT, POD, and SOD had boosted effects when irradiated at 10 kGy of gamma rays, however, they inhibit CAT activity. Determined that activities such as SOD, CAT, and POD can be stimulated in *Viciafaba L.* seeds when irradiated with gamma rays as they all effectively remove free radicals and prevent peroxidation of the lipid membrane. CAT inactivation leading to a drop in catalase activity is compensated by the APX activity, where H_2O_2 is decomposed by the activity of peroxidase. This research supports Pasternak (1987), who reports that cellular CA^{2+} levels are shifted due to peroxidase activity in the injured membrane. The gene expression of APX in cells is enhanced when low gamma rays are irradiated (Zaka et al. 2002). This research supported Foyer et al.'s (1997) findings that enzymes play a role in the upregulation of genes in enzyme activity.

Soybean seeds consist of a high amount of phenol content with wide use in pharmaceutical industries. Validated that antioxidants are affected inversely under different doses of irradiation. A low dose decreases the activity of CAT and GSH-Px, however, an increase in SOD, GPx, and LP is due to irradiation treatment taking place, even though nonenzymatic antioxidants did not affect soluble protein biosynthesis in soybean seeds. Irradiation of high dose, 200 Gy, stimulates oxidative stress and produces OH-ions. They showed that different antioxidant enzymes are activated depending on the amount of dose irradiated to defend the cell.

Vanhoudt et al. (2014) demonstrated the role of ROS-scavenging enzymes, SOD, CAT, ascorbate, peroxidase (APX), guaiacol peroxidase (GPX), and syringaldazine peroxidase (SPX) in roots and leaves of *A. thaliana* and reported that enzyme capacity gets affected in roots making them more radiosensitive. In contrast, leaves' enzymatic capacity is less affected making them less radiosensitive. He formulated that the GPX capacity of root starts to decrease even at a low dose of radiation as compared to leaves, whereas the GPX capacity of leaves was decreased when exposed to a high dose of radiation. The result showed that enzymatic activity at particular regions of plants also helps in tolerance against rays.

4.4 DNA Repair Mechanism

Energy absorbed and deposition of energy affects the biology of the cell due to ionizing radiations. Plant repairs the DNA by activating the cell cycle to look for damage in the cell (Cools and De Veylder 2009). Dose rate is important in the regulation of defensive mechanisms in the plant. When *Arabidopsis thaliana* was exposed to acute irradiations (1 Gy in 1 day) genes for DNA repair genes were activated as they play a role in regulating oxidative stress response and pathways of signal transduction. However, when *A. thaliana* was exposed to chronic irradiations (1 Gy in 21 days) the DNA repair and antioxidant gene's expression was not altered (Kovalchuk et al. 2007). Coyle et al. (2002) described that the plant cell in defense also produces certain antioxidants such as metallothioneins (MTs; metal binding protein); they hunt for hydroxyl radicals and actively prevent DNA damage. Furthermore, this research was proven, showing that MTs play a role in protection of creatine kinases by acting as chaperones against oxidative stress that inactivates enzymes (see Fig. 6).

Kam and Banati (2013) reported that mitochondrial DNA is more susceptible to ionizing radiation than the nucleus DNA. The DNA of mitochondria is damaged when part of the DNA is deleted as a result of radiation but it has the ability to overcome the damage by producing more copies of DNA to overproduce the mitochondrial proteins (Kam and Banati 2013). This elevated protein increases the production of superoxide as the activity of the electron transport chain is altered. Increased superoxide diffuses into other mitochondria that amplify the damage by signaling which further produces superoxide and eventually leads to the damage of nuclear DNA (Kam and Banati 2013).

Vegetables and fruits have antioxidants that have important health benefits and also act as free radical scavengers including polyphenols and ascorbic acid (Bland 1995; Surh 2003). Found that vegetables rich in ascorbic acids protect the plant against thymine oxidation promoted by gamma rays. Moon and Song (2001) found that ascorbic acid is helpful against gamma ray-induced ovalbumin and ovomucoid aggregation. Green onions are rich in ascorbic acids and are frequently exposed to gamma rays in increasing their shelf life and eliminating pathogens (Fan et al. 2003).

Dona et al. (2013) found that a variable dose rate of IR leaves different impacts on Petunia x hybrida cells' ability. A low ionizing dose is less effective in activating the protective DNA repair mechanism and ROS hunting. However, a high dose of gamma irradiations boosts Petunia's defense system. According to Pages and Fuchs (2002) DNA polymerase ensures the replication of DNA sections by assisting the replicative enzymes. This mechanism is more likely to generate high-frequency mutations (see Fig. 6). Dona et al. (2013) hypothesized that DNA damage with a low dose of gamma radiation was not completely repaired, as enzymes repair DNA lesions and create mutations afterwards. However, long-lasting irradiation maintains production of reactive oxygen species and the threshold that is required to activate the enzymes. However, acute irradiation causes severe stress—DNA damage—that activates the metabolic pathways and defense mechanism by attaining high activity of gene upregulation (Kovalchuk et al. 2007; Gicquel et al. 2011).

Jimenez et al. (2011) determined in their research that green onion having polyphenols and ascorbic acid, sacrificial radical compounds, are capable of preventing DNA damage by reacting with free radicals induced by gamma rays. The decrease in amount of ascorbic acid to 45 % (213 l M) in green onion from 364 l M after exposure to the radiation showed that they actively protect DNA (Jimenez et al. 2011). They formulated that the decrease in the amount of ascorbic acid after exposure to gamma rays for food preservation purposes reduces their nutritional properties.

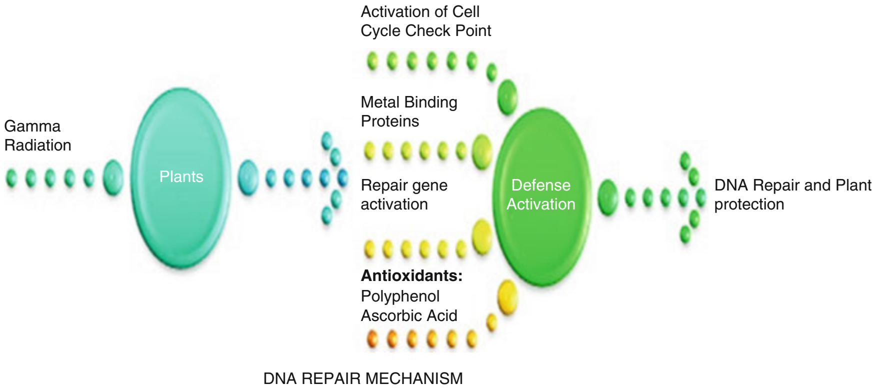

Fig. 6 DNA repair mechanism: gamma radiation results in activation of various plant defense pathways such as cell cycle check points activated and working to repair DNA (Cools and De Veylder 2009), metal binding protein called metallothioneins (MTs) starts hunting for hydroxyl radical to prevent DNA damage by chaperoning it. Antioxidants—naturally present in plants including polyphenols and ascorbic acid scavenge for free radicals—produced as a result of gamma rays and lethal to cells

Thus, ascorbic acid plays a significant role in protection of DNA due to its antioxidant nature (Jimenez et al. 2011).

4.5 Mutated Plants from Gamma Radiations

Mutagenesis is the process in which heritable changes occur in the genetic material that sometimes is repaired in the DNA repair process. Mutations are of two types; either occurs spontaneously in the DNA or is induced by various methods such as chemicals, radiation, or viral infections to make the genome adaptable to environmental changes. Gamma ray induction (physical mutagen) in causing mutation is widely used to improve crop production by creating diversity in the crops. On the molecular level these ionizing radiations are responsible for creating many types of mutations on the DNA base pair to chromosomal aberrations. According to the record of FAO/IAEA mutant varieties database, 3000 mutant crop varieties have been created by inducing gamma rays as a mutagen (Jain 2010).

Radiations are always considered harmful, but with proper care these radiations can help in bringing much advancement in plants by increasing genetic variability (Jan et al. 2012). With the help of advanced plant molecular tools and radiations crop productivity can be increased. Plants face changes in environmental factors as external stimuli that are induced as signals and affect plant physiology. With rapid change in climatic changes on a global level, and feeding the huge population, gamma rays for creating mutants can be handy (Jan et al. 2012). To make the plants survive all the environmental fluctuations certain radiations can help to enhance the germplasm of the plants (Jan et al. 2012). Any structural changes in DNA lead to functional changes, which are the result of DNA damage mostly after exposure to ionizing radiations. Variation in phenotype of an organism is the result of damage in the DNA molecule that causes altered gene expression. DNA modification ranges from changes in single base, substitution, and deletion, to epigenetic modification (Tanaka et al. 2010). Described that genetic stability in plants such as *Nicotiana tabacum* and *Arabidopsis thaliana* can be induced by homologous rejoining (HR) that helps to restore their normal genetic function by exposing them to acute or chronic radiation. Radiation exposure to plants results in homologous rejoining as the free radical production increases that activates the metabolism of *Arabidopsis*.

Ionizing radiations can be used as important tools to bring about genetic variability in breeding purposes. Recently, desirable traits or mutation efficiency can be increased using phenotypic molecular responses to IR (McKim and Hay 2010). Mutations bring varieties in crops and are used as a mode of genetic modification of useful fatty acid present in rapeseed. Successful rapeseed mutants have been developed using radiations (Bhatia et al. 1999). However, Erkkz and Allen (1961) concluded that success of mutant development depends on unchanged environmental conditions that keep the original genetic constitution unaffected.

Gorgidze (1980) described that irradiation by using gamma rays causes mutations in cultivated wheat that gets deviated from its normal path by increasing the chromosome number causing polyploidy in wheat, or by reversing the polyploidy to tetraploidy, morphological changes by aneuploidy, and many mutations in genes. Grain spike and weight were increased incredibly in generations after exposure to radiation (Gorgidze 1980). El-Shafey et al. (1991, 1993) describe that radiation by using fast neutrons helps in creating mutants by regeneration of the cell wall, and protoplast development. Much research also proved that the use of high neutron irradiation helps in developing high-yield cultivars (Duggal et al. 2000; Koebner and Hadfield 2001; and Al-Maaroof et al. 2003). But if the proper dose of radiation is not maintained, injurious affects can be seen on the plant, as it will inhibit plant growth ultimately leading to reduced production of the crop. Therefore it can be concluded that different doses of radiation help in deciding whether the rays will have a positive or negative impact (Kon et al. 2007). Described that a new form of species is generated when a low neutron acts to increase the protein concentration. Many studies also show that mutations induced by optimum neutrons result in generating variable phenotype varieties (Kharkwal 2001; Wu et al. 2005).

Nuclear technique uses are prominent in plant breeding; the majority of mutant crops created using irradiation include: beans, cotton, peanut, rice, barley, and wheat. However, FAO/IAEA establishment has led to the creation of 1800 cultivars produced by directly creating mutations or by crossing the mutant varieties (Maluszynski et al. 1995). Radioactive labeled probes in DNA recombinant have been used in creating transgenic varieties; in India rice-induced mutants (series "PNR") with high yielding properties were released (Chakrabarti 1995). In China for 10 years rice mutants "Zhefu 802" were grown. In 1977, in Thailand aromatic *indica* variety of rice RD6, a mutant created from gamma radiation was released. This variety was so successful that even for years after its creation it was grown in extensive regions of Thailand. *Japonica* rice mutant created by thermosensitive genic male-sterile mutation is induced by a single recessive gene caused by gamma radiation (Maruyama et al. 1991). These mutants show successful results and increase the yield of crop and are used as parent cultivars, for example, barley mutants "Diamant" and "Golden Promise" are used in the brewing industry in Europe and used as parent cultivars. In Pakistan "NIAB-78," a cotton mutant variety release sustained the textile industry in 1987. This cotton mutant variety has several features such as heat tolerance, and prevents bollworm attack during the early maturity stage (Green 1986; Dribnenki et al. 1996; see Table 2)

In China high-yielding peanut mutant varieties were released under the label "Yueyou" produced as a cross of mutant cultivars. India also released a similar peanut mutant variety "TG-26" with high production up to 9.4 t/h (Green 1986; Dribnenki et al. 1996). Gamma radiations are the efficient ionizing radiations that modify plant phenotypes to create improved mutant properties with high production of metabolites, and high productivity (Sato et al. 2006; Naito et al. 2005; Eroglu et al. 2007). These radiations are important in enhancing the production of secondary metabolites despite various biological damage it causes on the plant

Table 2 Crop mutants generated by gamma radiations worldwide

Crop variety	Modification	Country	References
Rice—Zhefu 802	High yield	China	Maruyama et al. (1991)
Rice mutant‘RD6’	Aromatic *indica*	Thailand	Maruyama et al. (1991)
Japonica rice mutant	Thermosensitive	Japan	Maruyama et al. (1991)
Cotton mutant “NIAB-78”	Texture, heat tolerant, and prevents bollworm attack	Pakistan	Green (1986), Dribnenki et al. (1996)
Peanut mutant variety—Yueyou	High yielding	China	Green (1986), Dribnenki et al. (1996)
Peanut mutant variety “TG-26”	High production	India	Green (1986), Dribnenki et al. (1996)
Centella Asiatic	Flavonoid contents		Moghaddam et al. (2011)

cell (Kim et al. 2005). Moghaddam et al. (2011) tested the flavonoid contents in control and treated plants of *Centella Asiatic*;, the irradiated plant showed a high concentration of flavonoid content with 8 weeks of the gamma radiation treatment of 20–30 Gy (see Table 2).

Demonstrated that a high dose of gamma radiation, 1200 Gy, reduces the quantity of oleic acid and generated mutants in rapeseeds with less genetic variability, and results in a high level of undesirable fatty acids, although low-dose gamma radiation, 800 Gys, produces mutants with high variability and also increases the amount of oleic acid in rapeseeds. Gamma radiations have been widely used in creating mutations in maize (*Zea mays*) and barley (Stadler 1928). High-yielding *Brassica juncea* mutant has been created by treating with gamma rays (750–1000 KGy); these rays are successful in creating stress-resistant varieties (Khatri et al. 2005; Wang et al. 2007a, b). Other research by Shah et al. (2001) reported the production of another high yielding and (*Alternaria blight* and white rust) resistant variety by exposure to high gamma rays (ranging from 1.0 to 1.2, and 1.4 KGy).

With all the climatic changes adversely affecting crop productivity, drought plays a chief role in limiting the yield of sugar beet (Donini and Sonnino 1998). Previously, Shah and Sharif (1994) reported the production of drought-tolerant sugar beet varieties by in vitro mutagenesis particularly by gel electrophoresis, and by molecular markers. However, in his findings created a drought-tolerant sugar beet mutant using gamma radiations in vitro culture, and confirmed his results using various biochemical parameters and isozyme variations. Genetic variability to create genotypes in a population helps to withstand various biotic and abiotic stresses (Uddin et al. 2007). Described that gamma radiations are a successful technique for creating drought-tolerant mutants in in vitro cultures when treated with 20 Gy of radiation. Induction of gamma rays causes changes in antioxidant enzymes that were detected using a spectrophotometer and by determining the level of isozyme variations, considered to be the reason for generating mutants from the ionizing rays, in control in treated sugar beet crop.

5 Beneficial Aspects of Radiations

Gamma rays have various applications in the medical, industrial, and agricultural fields. One of the common benefits of gamma radiations is the use of different doses in exploiting the agriculture field. These radiations are useful in bringing about genetic change, morphological or physiological changes, and biochemical changes by applying a different intensity of gamma ray dose. Plant breeding using different techniques helps to improve individual crop productivity by reducing disease incidence by various pathogens including viruses, bacteria, fungi, nematodes, and insects. The reduction of various diseases increases the yield of the crop and makes it better quality. However, the plant faces various stresses on a daily basis to improve and protect from various fluctuations; improving the genetic potential of the crop is important.

Nuclear techniques have broadened the scope of crop improvement in agriculture. Irradiated seeds result in genetic variation that allows plant breeders to improve and select new genotypic characteristics such as tolerance to salinity, improved yield and quality, and precocity. Consequently, gamma radiations are helpful in bringing about useful physiological characters (Kiong et al. 2008). Irfaq and Nawab (2001) started wheat improvement by mutation induction that improved the desired traits. Gamma radiations were applied in 1960 in North America for the purpose of food preservation. Gamma radiations are also used in food irradiation to eliminate harmful microorganisms, insects, fungi, and pests with doses up 1 kGy (Variyar et al. 2003) by creating harsh environment tolerant varieties (Al-Rumaih and Al-Rumaih 2008). Controlled exposure of gamma rays is still popular and is used for various purposes such as sterilization of medical equipment (Shokyu 2002).

Fan et al. (2003) and Niemira and Fan (2006) showed that shelf life of celery and other vegetables can be increased if the proper amount of gamma rays (1.0 kGy to 7 kGy) is applied that actively kills *Escherichia coli*. Aziz et al. (2007) described the uses of high doses of gamma radiation in sterilizing the seeds from all kinds of microbial contaminants; there are many reports on gamma rays as a fungicidal agent. Low energy doses of gamma rays (0.15 kGy) are beneficial in the storage of onion by inhibiting sprouting (Niemira and Fan 2006). Described the importance of gamma radiation in extending the shelf life of fruits and vegetables that helps in reducing the decay time of the edibles. These radiations are quite known for their sterilization ability to prevent the colonization of various bacteria and provide durable protection to perishable vegetables against insects. Gamma rays are also used in the storage of fruits to prevent spoilage caused by fungal pathogens by maintaining the proper physiology of the fruits. Determined the useful role of gamma rays against nematodes *Botryosphaeriadothidea, Botrytis cinerea,* and *D. actinidiae* in kiwifruit.

Mashev et al. (1995) described the use of gamma rays in wheat that can help to reduce height to tolerate windy environments and to prevent lodging; that can reduce the annual loss of the wheat crop by increasing the yield. The high irradiation dose of gamma rays of about 5000–15,000 not only reduces plant height but increases the efficacy of wheat to give better and higher yields by increasing the content of proteins and essential amino acids over the nonradiated plant (Mashev et al. 1995). However, Din et al.'s (2003) results on different wheat varieties found that an increased dose up to 35 kGy can induce abnormalities in wheat. Nevertheless, concluded that increasing the dose can help to improve the physiology and morphological characteristics of the wheat crop. The rays were found to improve wheat height with increased yield by improving the number of ear-bearing tillers.

Millet crops are a main focus of public authorities due to high fungal and mycotoxin contamination that causes massive loss in its production (ISO Standard 6322-1 1996). Various methods have been incorporated to sustain the trade of crops and by innovating preservation technologies. Methods for decontamination by using various fumigation products, ethylene oxide or methyl bromide, are at its peak along with radiations especially gamma rays. Use of gamma radiations at 1–10 kGy in preservation and decontamination of microorganisms is the most promising and safest process that at the same time works to improve the shelf life of millet flour (Codex Committee on Food Additives and Contaminants 2001; Aziz et al. 2006). Optimum amount and time period of gamma radiations exposed to the bulk of food products helps in controlling and preventing microbial growth, and slows down fruit maturation by preventing biochemical reactions taking place during maturation (Singh and Pal 2009). Optimum selection of radiation is very important as some radiations have toxicological side effects and result in production of toxin that further reduces the freshness of the crop and increases the degradation of organoleptic properties, decreasing the nutritional content of the food (International Atomic Energy Agency 1999).

Ferreira-Castro et al. *(*2007) described that among all the treatments used for the decontamination of the millet crop, irradiation by using gamma rays was the most promising. They evaluated effects of different doses ranging from 1 to 5 kGy on millet flour that proved to reduce the presence of many pathogens including bacteria, yeast, and mould. Lapins (1983) reported that gamma radiations are useful in enhancing physiological characteristics. Gamma radiations are considered to be disinfectant for microbial treatment and are widely used to enhance biochemical properties of millet flour at 2–3 kGy and increase shelf life (Ferreira-Castro et al. 2007).

UV light in addition to being harmful also has some advantages. There are many studies reporting the use of UV light against plant biotic stresses and in increasing the crop's productivity. Nevertheless if UV light can be used effectively and its disadvantages can be controlled, it can prove to be quite beneficial. A major benefit of UV is its effect against plant pathogens that are known to affect crop quality and yield. UV light is used as a biological control that provides protection to plants from fungal, bacterial, and viral pathogens. Because pathogens are sensitive to high levels of UV, they can serve as an effective biological control to counter pathogens (Paul and Gwynn-Jones 2003). It has been reported that growth of fungal pathogens are severely reduced in the presence of UV due to a decrease in germination of fungal spores and mycelia growth (Willocquet et al. 1996; Jug and Rusjan 2012). Those environments that have reduced UV exposure can also lead to reduction in insects such as whiteflies but this can result in the major reduction of insect pollinators thus affecting pollination and seed dispersal of plants (Paul and Gwynn-Jones 2003).

UV is also known to increase the growth of commercially valuable crops by increasing the length of stems, by improving flower colors of ornamental plants (Oren-Shamir and Levi-Nissim 1997), and by improving seed ripening (Bacci et al. 1999). This can be made possible by growing the plants under such chambers and greenhouses that transmit UV light. UV light can also be used to increase nutraceuticals in plants by increasing their phenolic content, terpenoids and alkolids. It can also be used to increase a plant's capacity to make industrial products and herbal medicines (Hajnos et al. 2001). In a study on grapevine, it has been shown that increase in the production of antioxidants due to UV-B stress and accumulation of secondary metabolites such as flavonoids can give advantages to human health including providing anticancerous drugs and by providing protection to the cardiovascular system of humans (Dzhambazova et al. 2011). Increased UV levels are also known to stimulate the concentration of stillbenes that are also beneficial for human consumption (Jug and Rusjan 2012).

Another study on *Lactuca sativa* has been reported that showed an increase in plant growth rate if UV light is steadily provided to the plants. However, if a high and sudden exposure on the plant is done, the plant growth decreases (Wargent et al. 2011). Hence UV can provide little benefits to humans to protect the crops against biotic and abiotic stresses. A better study on the application of UV to plants especially postharvested crops may lead to improved nutrition that can be ultimately useful for humans (Wargent and Jordan 2013).

6 Future Perspective and Conclusion

Ionizing radiation has various aspects in all applied fields. Gamma ray usage in improving the shelf life of fruits and vegetables to the sterilization of microbial contaminants are quite prominent. They help to delay ripening and browning of fruits, and improves their quality. They are beneficial in controlling fungal diseases in postharvested crops. Radiations are used instead of chemical fumigates to treat fungus in seeds (Paul and Gwynn-Jones 2003). Resistance to UV radiation in crop plants has increased the yield. Introduction of the photolyase gene in crop plants can make plants resistant to UV radiations (Yoshihara et al. 2005). More efficient studies on cell cycle regulation need to be done that can provide strong proof of UV-B effect on crop productivity. The effect of UV-rays on postharvest crops can help to improve nutrition, and also has increased nutraceuticals in plants by UV radiation. The role of radiations in creating mutants and radioactive agents pave new ways in creating different aliments.

Arora et al. (2005) described the development and potential use of radiation-protected plants in treating various diseases. Radiation-protected mutant plants are expected to protect against radiation damage, therefore, these plants can be helpful in treating ailments caused by the production of free radicals. Consequently, development of new drugs from plant extracts in treating radiation injury can lead to novel advancement of health sciences. Further studies, development, and application of drugs using bioactive compounds can make a possible difference in treatment with fewer side effects (Arora et al. 2005).Driscoll et al. (2014) described the advances in the use of ionizing radiations in wood biomass. The biomass of wood is widely distributed throughout the world and has an important role in various applications, especially the hemicellulose and lignin being abundant synthetic polymers, and has various applications in the paper and lumber industries. But the woody biomass in fuels and chemicals requires undergoing proper treatment before their usage due to their crystalline nature; this method increases their usage in defined industry. Induction of gamma rays breaks the bond and initiates the chemical reaction. The use of gamma rays in this method can be helpful to integrate the use of woody biomass into many fields (Driscoll et al. 2014). Keeping the negative impact of radiations in view, further advancement and studies can help to make the proper use of these rays in various fields beneficial for mankind.

Earth is constantly facing radiations; depletion of the ozone layer has resulted in absorption of harmful rays into the Earth's surface. Among all radiations, UV rays and gamma rays are considered to have negative impacts on the living organisms of Earth. Hence UV-B can affect many physiological, biochemical, and molecular pathways inside the plant. Crop plants have evolved to defend themselves from UV-B stress by initiating DNA repair mechanisms and the flavonoid biosynthesis pathway. They can also change their morphology and limit the rate of photosynthesis and prevent photosynthetic pigment alterations and changes in biomass. These protective mechanisms can prevent crops from losing their quality and yield but are still not effective if crops are exposed to high levels of UV-B. Therefore improvement of the crop's defensive mechanisms is the utmost requirement so that crops can be protected against light radiation stresses. Similarly, exposure of gamma rays affects seed germination, plant growth, cellular structure, and biophysical content present in plants. Ionizing radiations have detrimental effects on photosynthesis by affecting the function of PSII. Nevertheless this radiation if maintained and delivered at a proper doses boosts the antioxidant enzymes by protecting plants against radiation. Despite much irreversible damage caused by radiation, gamma rays can still be considered to improve the genetic variability of the crop to increase sustainability of crops. Rapid and harsh fluctuations in the environment have increased stresses in plants, therefore, creation of diverse mutants can help in increasing the yield.

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