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The Effects of Light on Photosynthetic Machinery and The Development of *Camellia sinensis* (Tea Plant): Review

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Abstract

Camellia sinensis is one of the major commercial crops that is broadly grown in many countries such as Asia, Africa, and Latin America. It is utilized in the production of beverages that are non-alcoholic and consumers friendly. The leaves of tea plants are green, but during the plant evolution under environmental stress, a variety of complex mechanisms are developed, leading to variations in leaf color. The tea plant is considered to be a light-sensitive plant. In this review, we summarized the mechanism of how light has crucial effects on the photosynthetic machinery of the tea plant and the accumulation of specialized metabolites such as carotenoids, flavonoids, caffeine, and chlorophyll which ultimately affects its development. There is a strong correlation between light intensity, photosynthesis, and the development of tea plants. High intensity of light induces changes in phytochrome which inhibit the chlorophyll synthesis in tea plants due to the photosensitivity of chlorophyllide an oxidase and coproporphyrinogen III oxidase; leaf etiolation can worsen while under the moderate shade, the color of the leaf turns to green, the accumulation of chlorophylls and Carotenoids biosynthesis also increases under medium shade, due to upregulation of supreme carotenoids-regulating genes, while extreme shading downregulates them, which offers a significant approach for tea plant cultivation and marketing.

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Introduction

Tea (*Camellia sinensis*) is a member of the family Theaceae. There are 82 species in Genus *Camellia*. *Tea* has been ranked as the second consuming beverage globally after water (Ho *et al.,* 2009). Tea is considered the most favorite, favored refreshment drink or beverages that are non-alcoholic and consumer's friendly that is globally consumed (Zeng *et al.,* 2018). There are various secondary metabolites present in the leaves and buds of tea shoots, such as vitamins, fibers, tannins, sugars, lipids, proteins, saponins, amino acids, and minerals, theanine, polyphenols, and volatile oils and alkaloids (Weerawatanakorn *et al.,* 2015).

According to Xu and fellows (2021), usually, the leaves of the tea plants are green, but during the plant evolution under environmental stress, variations in leaf colors arise. Shin and co-workers (2018) demonstrated that the plants of tea have green leaves by nature, although certain variations in leaves colours, i.e., albino, violet, and etiolated, have been observed. According to Song and colleagues (2017), Purple, white and yellow colors can be found on stems, leaves, and buds. Higher levels of amino acids are present in leaves and buds of the tea mutant albino and etiolated than green ones, which grabbed the attention of producers and consumers.

High-quality breeding materials include albino, etiolated, and purple tea plants. The pigment accumulation pathways in these tea plants differ depending on the environment, resulting in leaves that are white, yellow, purple, or a mix of colors. These are classified as Tea assets that are temperature or photosensitive based on various inducing factors. The majority of tea plants are photosensitive. When exposed to bright light, the leaf color is yellow. When under shade, the leaf turns into green color, and etiolation is reduced. The genomic profile, a few particular mutations, and disparity accretion of bioactive molecules in light-sensitive tea cultivars are slowly elucidated. Biosynthesis and metabolic regulation of bioactive complexes are different, under various light conditions (Yue *et al.,* 2021). In this review paper, we summarize the advancements in the current research on the effect of light on the development and photosynthetic machinery of *Camellia sinensis*. We also extensively sum up the leaf shading mechanism because of signals of light in tea cultivars for profoundly or methodically comprehending staining the components of photosensitive etiolated tea assets. It gives a hypothetical premise to takin functional light control lengths to utilize qualities of etiolated tea assortments.

The effects of light on the development of tea plant (Camellia sinensis)

According to Qian and co-workers (2009), light is a vital ecological element to control the development and advancement of plants. Light isn't just a fundamental energy source for plants. It is also a significant sign of the influence of progress of the plant's seedling between etiolation and de-etiolation. According to Anna *et al.* (2001), It plays a vital role in plant control, in the form of the intensity of light, photoperiod, the quality of light, as well as being a regulator for plant development, physiological metabolism, morphogenesis, cell component biosynthesis, and epigenetics throughout the plant's life cycle. The growth of plants, photosynthesis, yield and the quality of plants are greatly affected by the quality of light. By decreasing the intensity of light during plant development, biological traits, i.e., the height of plants, diameter of the stem, the structure of a leaf, leaf color, and area of leaves are dramatically altered, as a change in photosynthetic contents and photosynthetic efficiency. The impact of different light qualities on plant development is distinct. Red light is crucial for the development of the photosynthetic apparatus, inhibits photosynthetic diffusion, and enhances the accumulation of starch. The development of chloroplast, the formation of chlorophyll, and the opening of stomata are all influenced by blue light. (Senger, 2008). Light has a strong influence on the agronomic characteristics, biochemical and physiological properties, and internal structure of the tea plant. Due to the intense light, a tea plant grown in full light will have thick, brittle, hard leaves and a small leaf shape, with short internodes. Tea plants have large leaves shapes, soft and thin leaves with long internodes. Under the moderate shade, physicochemical characteristics of the tea plants were altered. Compounds containing Nitrogen, i.e., amino acids and caffeine, were increased under the shaded area. Carbon-containing compounds like fiber, polyphenols, and carbohydrates were reduced under the shade. Sponge tissues were mainly arranged loosely and wax layer thickness was also declined when the tea plant was kept under the shade (Wan, 2008). According to Ai *et al.* (2017), various monochromatic Lights are used to pre-harvest the fresh tea plant leaves in order to enhance tea taste. Lee and co-workers (2013) concluded that sunlight is vital for the physiological growth of the light-sensitive tea plant's leaves. The grana of the mottling tea "Baijiguan" was sparse during higher intensity. The shape or periodicity of the thylakoid membrane system is also disrupted (Wu *et al.,* 2016).

Light sensitive signals in tea plants

The specific information of transduction photoreceptor cells entrusts plants with formative plasticity for light signals. Plants could sense, accept, and transfer light signals thru the various photoreceptors and afterward control the operating mechanism of correlating genetic media to accomplish the respective series of chemical reactions under various light signals (Briggs, 2001). There are five phytochromes in higher plants, two cryptochromes, one superpigment, and one is phototropin; these are the major photoreceptors (Carabelli *et al.,* 2010). Red-light (λmax = 660 nm) and Far-redlight (λmax = 730 nm) are 2 types of phytochromes. For the Red color's light, absorbing form is Pr. It is most stable and called inactivation physiologically. For Far-redlight, Pfr is absorbing form. They can transform into one another by the isomerization of chromophores. It is called physiological activation (Gu *et al.,* 1997).

In angiosperms, there are 3 major phytochromes present, i.e., Phytochrome PHYA, PHYB, PHYC, and they are encoded by *PHYA*, *PHYB*, *PHYC* genes. There are 2 additional phytochromes, i.e., PHYD and PHYE found due to the event of gene replication in dicots (Mathews *et al.,* 2010). While in tea plants, PHYD is not present (Mo *et al.,* 2019). According to Moon and fellows (2008), PHYA is additionally sensitive to white light and it is found in etiolated tissues. While in the lighted tissue Photolabile, PHYC & PHYB were found. According to Kong and colleagues (2018). Biosynthesis of carotenoid and in photomorphogenesis PHYA and PHYB were involved. It interacts with Transcription factors helix-loop-helix bHLH which generate PIFs, PIF1-PIF5 phyinteracting interacting factors. They regulate the pigment compound's metabolism by binding to promoters (Quian-Ulloa *et al.,* 2021). According to Moller and fellows (2002), The intensity of light affects the agronomic traits, flavor, and yield of tea plants. According to Kreslavski and fellows (2018), various conditions of light have diverse phytochrome genetic regulations, which lead to alteration in the system of photosynthesis and the development of tea plants.

According to Park and co-workers (2018), PHYA is involved in the higher light reaction under far light, while PHYB and PHYC are involved in lower light radiations and transitions across far-red light and red (Franklin *et al.,* 2005). The production of chlorophylls is controlled with the light signals. Chlorophyll a and b ratio varies under different qualities of light Conditions. chlorophyll-b produced under the influence of blue light and yellow light while red light involves in the biosynthesis of chlorophyll-a (Zhou *et al.,* 2006; Wan, 2008). According to Kong and fellows (2018), carotenes are the precursor of the terpene fragrance constituents as well as specialized photosynthetic pigments in the tea plant.

Factors affecting the leaf colour of the light-sensitive tea cultivars

The colour of leaves of the tea plant is determined by the relative concentration, absolute content, and dispersal placement, while genetic factors are critical factors in the tea plants. Due to different ecological factors, expression and regulation of protein transport characters as a result of differences in nuclear genes or chloroplast genes (Zhang *et al.,* 2020). Tetrapyrrole compound Chlorophyll, which includes chlorophyll a and b is widely present in plants. These are the major photosynthetic pigments of plants. Chlorophyll a is blue-green, while chlorophyll b is yellow-green (Fromme *et al.,* 2003). According to Tanaka and fellows (2007), they absorbed light energy, converted, and redirected in the reaction center. Carotenes are fat-soluble pigments. It is a type of polyisoprene pigment that is integrated with the chloroplast and chromosomal membrane and has a primarily yellow and orange appearance. It contains alpha and beta carotenes and xanthophylls, which are very conventional in the plant's classification. It contains β, β-xanthophylls violaxanthin, antheraxanthin, β, ε-xanthophyll lutein, zeaxanthin, and neoxanthin. Carotenoids have the ability to stabilize compounds of photosynthesis by binding them and enhancing the efficiency of chlorophyll-binding proteins to collect light. Carotenoids protect chloroplast from light; they are also called complementary pigments (Cazzaniga *et al.,* 2012). According to Hu and colleagues (2014), Anthocyanins and xanthin are mainly classified as Flavonoids; they are also called anthocyanins. They show different colors in different environments, i.e., in it appears blue in alkaline environments and red colour in acid environments.

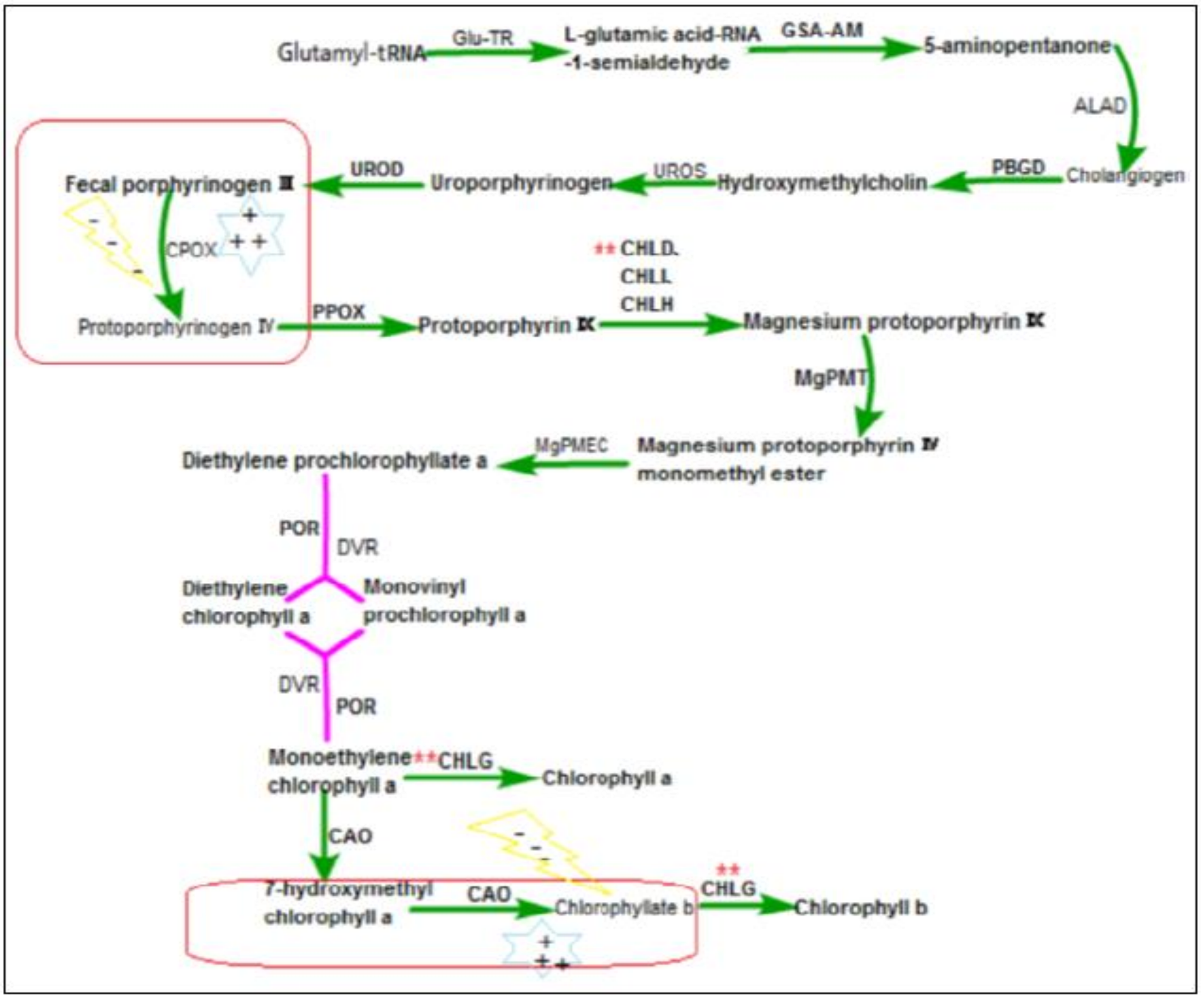

Fig. 1. The pathway of biosynthesis of chlorophyll in the Tea plant (Yue et al., 2021).

Anthocyanins are responsible for purple color in a leaf of tea cultivar, whereas lutein, quercetin, and myricetin seem to be yellow-colored pigments that play a role in the yellow color of tea leaves (Wang *et al.,* 2017; Fan, 2019). Biosynthesis of pigments of photosynthesis in the etiolated tea variety is fewer than the other varieties of conservative green tea because it has less chloroplast in mesophyll cells with lower grana lamellae. Photoinhibition occurs during the summer when the intensity of light is high. It causes the yellowish color of leaves due to disruption in the development of chloroplast (Tian, 2020), the formation of saccular vesicles, a gradual increase in vacuoles, and the reduction in carotenoid and chlorophyll contents (Xu, 2016).

The effects of light on the photosynthetic machinery of the tea plant

According to Han and co-workers (2018), In plant cells, light stimulates variation in photosynthetic pigments and elements; for example, red light increases the formation of chlorophyll in peanuts and encourages the carotenoid's accumulation in the leaves of tomatoes (Mengmeng *et al.,* 2014). Light of Blue color plays a vital role in chlorophylls accumulation and carotenoid regulation in lettuce (Anna *et al.,* 2001). Red-blue light is vital for the treatment of chrysanthemum seedling and biosynthesis of pigments in cucumber (Tang *et al.,* 2011; Kim *et al.,* 2012).

Biosynthesis of carotenoids and chlorophyll are enhanced under the exposure of red-blue light in spinach leaves which indicates that it is responsible for phenotypic variations in leaf color (Huang *et al.,* 2018). Li and fellows (2016b), in their study, concluded that Photoreceptors are varying from plant to plant, which is the major cause of etiolation in plants; for example, in Huangjinya, Huangjinju, and Huangkui, chlorophyll and carotenoids are absent. Photoreceptors are involved in chlorophyll's synthesis. Synthesis of Chlorophyll begins with glutamyl-tRNA and progresses through chlorophyll a and b. It has three events: (1) Glu-tRNA to 5-aminopentanone (ALA), (2) AlA to magnesium protoporphyrin IX, and (3) AlA to magnesium protoporphyrin IX. On the chloroplast matrix, the procedure is done. Magnesium protoporphyrin IX convert chlorophyll a and chlorophyll b, while in thylakoid membrane, chlorophyll a and chlorophyll b are produced (Gupta *et al.,* 2014). The process of catalysis required fifteen enzymes (Ernesto Bianchetti *et al.,* 2018). These enzymes are encoded by 27 genes that have been yielded from Arabidopsis (Beale, 2005). The crucial enzyme is magnesium chelatase subunit D (CHLD). While there are two vital regulatory genes are (1) CHLP (geranyl diphosphate reductase gene) and (2) CHLG (chlorophyll synthase gene). Changes in the coding gene of enzymes during the synthesis of chlorophyll can influence the enzyme's attributes, which reduce chlorophyll synthesis.

If mutations occur at an early stage, it results in leaf colors changing from green to yellow and white color. When they occur in later stages of development, then leaves seem to be spotted and striped (Sakuraba *et al.,* 2013). According to Feng and fellows (2019), Plants show photoinhibition underexposure to high intensity of light, which reduces the chlorophyll synthesis (Shi *et al.,* 2005). The majority of plants have no ability to produce chlorophyll in the dark. This phenomenon mostly occurs due to differences in gene expression of chlorophyll, synthetic genes under various intensities of light. When plants are green, light induces Mg-chelatase, which is encoded by *CHLD, CHLH, CHLI2,* and *CHLI1* genes (Stephenson *et al.,* 2008). Under the irradiation of light, the activity of Mg-protoporphyrin IX methyltransferase (MgPMT) is rapidly increased, which is encoded by *CHLM* and expressed in tobacco and barely, histochemically (Stenbaek *et al.,* 2010). According to Tzvetkova and co-workers (2007), under the high intensity of light, light induced-proteins are enhanced. They decrease the free chlorophyll synthesis by reducing the activity of subunits CHLI1 and CHLH of GluTR and Mg-chelatase. Zhang and fellows (2015), in their study, demonstrated that the intensity of light influences the anabolism of chlorophylls among both mitochondria and chloroplast via metabolic signals.

Photosynthesis-related gene 10 kDa protein gene (*PsbR)* in photosystem II has inhibited underexposure to the high light resulting in a reduction in the synthesis of chloroplast and development due to damage in photosystem II (Suorsa *et al.,* 2006). When they are kept in shade, it restores the structure of chloroplast by the up-regulation in the expression of *PsbR*, which decreases the photooxidation disruption (Wu *et al.,* 2016). In the pathway of biosynthesis of chlorophyll, under the high light, geranylgeranyl reductase and protochlorophyllide oxidoreductase (POR), which are encoded by *ChlP* and *POR* can induce which affects the chlorophyll synthesis (Dong *et al.,* 2018). The impacts of light on the development and the synthesis of chloroplast of tea cultivars are parallel to Arabidopsis (Pattanayak *et al.,* 2011). *POR* expression inhibition plays a vital role in the phenotype changes in the leaves of the tea plant (Zhou *et al.,* 2013).

According to Ma and co-workers (2018), the expression of *STAYGREEN SGR* is the major cause of tea leaves chlorosis because this gene is responsible for chlorophyll degradation. Two points of blocking of chlorophyll synthesis are found in the leaves of "Huangjinya", under high light intensity (Fan, 2019). While another point is Pchlide to chlorophyllide b, they are also inhibited under high light (Yangen *et al.,* 2019). According to Li and fellows (2013), In the etiolated tea plant, the Myb Avian Myeloblastosis Viral MYB family is also responsible for the regulation of gene expression. Liu and co-workers (2014) demonstrated that the efficiency of photosynthesis is decreased due to the destruction of chloroplast organs and levels of chlorophyll by the greater expressions of both *CsPHYA* and *CsPHYB* genes, which enhance phytoene synthase (PSY) silencing in etiolated tea leaves underexposure of red light (Tian *et al.,* 2019). According to Jiang and co-workers (2020), Chloroplast enhancement is reduced under high intensity of light, while when light intensity decreases, the development of chloroplast, grana accretion and ultrastructure of Thylakoid Membrane enhances the synthesis of chlorophyll in the tea plant (Liu *et al.,* 2017, 2018). According to Quian and fellows (2021), the Biosynthesis of Carotenoids starts with the accrual of isopentenyl diphosphate (IPP) and, afterward, dimethylallyl diphosphate (DMAPP). Zhang and co-workers (2020) concluded that the Catalysis of geranyl diphosphate synthase (GGPPS) produced geranyl diphosphate (GGPP). PSY catalyzed 2 GGPPs.

Lycopene is produced for the synthesis of the first carotenoid by the Phytoene desaturase (PDS), ζ-carotene isomerase (Z-ISO), carotenoid isomerase (crtISO). The 1st vital enzyme in the process is PSY. It is an important regulator for the synthesis of carotenoids (Toledo *et al.,* 2010). According to Kawabata and fellows (2014), the photosystem, excess chlorophyll in the excited state decomposed by zeaxanthin, which scavenges oxygen free radicals of oxygen (Jahns *et al.,* 2012). The PHYB is induced by the white light causing, HY5 to be released from compounds DDB1/, COP1/, and CUL4. In contrast, PHYB phosphorylates PIFS, at the same time resulting in degradation by the proteasome 26S. This leads to the accumulation of HY5, which binds to LRE in the promoter region of PSY, inducing carotenoid synthesis (Rausenberger *et al.,* 2010).

The expression of flavonoid biosynthetic genes decreases under shade while increasing the expression of carotenoid biosynthetic genes. It indicates that the pathways of synthesis of carotenoids and flavonoids differ in how tea leaves discolor (Sano *et al.,* 2018). According to Song and fellows (2017), Under the high intensity of light, the regulation of all the carotenoid biosynthetic genes is reduced, while under the moderate intensity of light biosynthesis carotenoid is enhanced (Quian *et al.,* 2021). According to Toledo and co-workers (2010), Photoreceptors are not activated in the cytoplasm under dark conditions, which inhibits carotenoid biosynthesis. Anthocyanins protect plants by the absorption of UV-B radiations, which cause destruction. These are water-soluble pigments present in tea plants in the form of glycosides (Mei *et al.,* 2021). Anthocyanin is found in high concentrations in Ziyan and Zijuan tea varieties which have red and purple leaves and buds (Mei *et al.,* 2021). The levels of anthocyanin affect the phenotype of the tea plant's purple leaf and bud (Li, 2014; Sun, 2016; Shen *et al.,* 2018).

The accumulation of crucial factors involved in leaf color of light-sensitive tea cultivar under various intensities of light

Tea leaves' color is a vital indicator of their quality (Taylor *et al.,* 2010). According to Tian (2020), the level of etiolation and the intensity of light of the light-sensitive tea have a strong relation. This mutant's unique color is considered a new commercially valuable trait. According to Wu and fellows (2016), it is quite possible to burn and disturb the bud whenever the intensity of light exceeds the limit of light intensity. According to Zheng and colleagues (2021), the absence of chlorophyll and carotenoid content in "Baijiguan" and other tea assets causes the yellow trait of tea leaves, which enhances its vulnerability to ultra-violate stress.

Li and co-workers (2016a), in their study, concluded that there is a decrease in gene transcriptional levels that regulate carotenoids and the biosynthesis of chlorophylls in "Huangjinya" than "Fudingdabai" when exposed to normal Slight. While under moderate shade, genes regulation is increased, which shows that the high intensity of light inhibits the chlorophyll and carotenoid's biosynthesis. Leaf's color in "Huangjinya" changes when exposed to distinct wavelengths of light, demonstrating that blue or white light efficiently retains leaf yellow coloured, whereas red light turns the leaf green (Tian *et al.,* 2021).

According to Ernesto and fellows (2018), there is one more hypothesis for why monochromatic light impacts the shade of "Huangjinya" leaves is that red light energizes chlorophyll combinations. Photoreceptors are involved in chlorophyll synthesis.

According to Xu (2016), the photochemical reaction is greatly influenced by the quality of light because of the distinct light-absorbing efficacy of various strains of photosynthesis. According to Hoffmann and colleagues (2015), under the exposure of red and blue light (400–510 nm), the photomorphogenesis of "Huangjinya" shows higher NPQ values instead of white light. It shows that for the protection of photosystem II from disruption, photoinhibition and greater consumption of energy are required. Photosensitive etiolated tea plants have low concentrations of carotenoids and chlorophylls.

However, these levels can be enhanced because the regulation of carotenoid biosynthetic genes enhances under moderate shade (Yue *et al.,* 2021).

Conclusion and future perspectives

In this review paper, we summarize the recent advancement in research on the effect of light on photosynthetic machinery and the development of the tea plant. We focused on the etiolated tea plant, which is a tea mutant and shows variations under different light intensities as well as the factors which induce phenotypic variations in the leaves of tea plants. In this study, accumulations of various pigment compounds under different light intensities are discussed, as well as their mechanisms. The light-sensitive etiolated tea plant is an outstanding mutant tea asset that can be used to make green tea that is tailored to market preferences.

The leaf colour is controlled by the amount of light it receives. However, Inadequate light easily retard stress tolerance, photosynthesis, and chlorophyll content of the leaf, which is a major cause of leaf burn or color change to green.

We have a complete understanding of the "administration" of light in the leaf traits of the mutated cultivars. It is beneficial in resolving this issue why to retain the physiochemical attributes of the mutated tea plant while avoiding destruction from the intensity of light, thus enhancing the yield of Tea crops. Carotenoids and Chlorophylls are found in light archive compounds in plants that have effective photosynthetic activity. They can impact the development and improvement of tea plants, as well as the formation of bioactive molecules and the regulation of leaf color in responding to light environments.

The study of the light-sensitive signals of the tea cultivars is nevertheless in the early stages. More research studies are required to comprehend the mechanism of the effects of various light intensities on tea plants effectively. Tea plants with various leaf shapes have had their genomes decrypted. In the future, we will investigate the gene transformation mechanism of tea plants, investigate the light-sensitive mechanism in tea cultivars thru various phenotypes, increase our knowledge about tea cultivation production, and introduce new varieties of tea cultivars that can show more stress resistance, enhanced flavor and can give more yield.

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Author's contribution

Samina Kausar, conceptualization, methodology, analysis, manuscript writing, original draft writing, editing, and reviewing. Rana Badar Aziz helped in writing The Effects of light on the photosynthetic machinery of the Tea plant. Isbah Akhtar helped in writing the effects of light on the development of *Camellia sinensis* (Tea Plant). Fakhar-E-Alam helped in writing Factors affecting the leaf colour of the light-sensitive Tea cultivars. Muhammad Rashid helped in manuscript editing and proofreading. Muhammad Abdul Haseeb helped in abstract writing and proofreading. Sadaqat Ali helped in writing Light sensitive signals in tea plants. Mansoor Hameed, assisted in the finalization of the research idea, supported in writing, proofread, and approved the final manuscript. Muhammad Usman Shoukat, software and help in the drafting of the manuscript.

Conflict of interest

The authors have declared no conflict of interest.

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