Light-sensitive Albino Tea Plants and Their Characterization

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Abstract. Albino tea plants are mutants that grow albino young leaves owing to lack of chlorophylls under certain environmental conditions. There are two types of albino tea plants grown in production, i.e., light- and temperature-sensitive albino tea cultivars. The former grows albino leaves in yellow color under intensive sunlight conditions and the latter grows albino leaves with white mesophyll and greenish vein as the environmental temperature is below 20°C. Both albino teas attract great attention because of their high levels of amino acids and the “umami” taste. There have been many studies focusing on the temperature-sensitive albino tea plants, whereas little attention has been given to the light-sensitive albino tea cultivars. The characteristics of the albino tea cultivars and the mechanism underlying them were reviewed in the present article based on the published literatures, including chemical compositions, morphological characteristics, and molecular genetic mechanism.

There is great genetic variation in tea germplasm, among which albino tea plants are mutants that grow albino young leaves owing to lack of chlorophylls under certain environmental conditions (Du et al., 2006). The albino tea cultivars attract great attention owing to their high level of amino acid concentration and especially the “umami” taste and fragrant aroma (Li et al., 2016b). There are two types of albino tea plants found and used in production, i.e., temperature-sensitive and light-sensitive albino cultivars (Wang et al., 2015).

The temperature-sensitive albino tea cultivars grow “white” albino young leaves because of their reduced chlorophyll biosynthesis as environmental temperature is below 20 to 22°C in the early spring, but their chlorophyll biosynthesis resumes and the leaves become green as common tea cultivars when the temperature rises above 20 to 22°C in the summer and autumn seasons (Li et al., 1999). Light-sensitive albino tea cultivars grow young albino leaves under intensive sunlight conditions in the Summer and Autumn seasons (Wang et al., 2008). The temperature-sensitive albino tea leaves have been used in production since the 1980s and there were many researches focusing on it (Du et al., 2008, 2009; Feng et al., 2014; Li et al., 2016a, 2016c; Wei et al., 2012; Xiong et al., 2013; Xu et al., 2017; Yuan et al., 2015). Whereas the light-sensitive albino teas were discovered in recent 10 years and there are many technical issues remaining to be solved during production, such as the low survival rate of the transplanted tea plants due to low photosynthesis capacity and the damages induced by strong sunlight in the summer (Li and Kong, 2010). Based on the published literatures, characterization of the light-sensitive albino tea plants was reviewed in the present article, including their morphological and chemical characteristics as well as molecular genetic mechanism of the albino induced by light.

Chemical Composition

Amino acids, catechins, and caffeine are important components with regard to the sensory quality of green tea (Liang et al., 2008). Light-sensitive albino tea cultivars such as Yujinxiang, Huang-2, Huang-8, and Huang-13 contain higher amino acids but lower total catechin levels than normal tea cultivar Fudingdabai. There is no significant difference in total catechins between temperature-sensitive albino tea cultivar Baiye-1 (its former name was White leaf No. 1) and normal cultivar Fudingdabai although the former has higher level amino acids than the latter. Compared with temperature-sensitive albino tea cultivar Baiye-1, the light-sensitive albino tea cultivars have less total catechins although both amino acid levels are higher than normal tea cultivar Fudingdabai (Table 1) (Li et al., 2016d, 2016e).

Chlorophylls and carotenoids are important pigments in plants which play a key role in photosynthesis and coloration of leaves. Both light-sensitive and temperature-sensitive albino tea cultivars have much lower levels of chlorophylls a and b than normal tea cultivar such as Fudingdabai. Among the albino tea cultivars, the temperature-sensitive albino tea plants usually grow leaves with albino mesophyll and greenish leaf vein. That is why the temperature-sensitive albino tea plant has higher level of chlorophylls than the light-sensitive ones (Table 1). Carotenoids serve two key roles in plants, i.e., absorbing light energy for use in photosynthesis and protecting chlorophylls from photodamage (Armstrong and Hearst, 1996). Carotenoids are classified into two groups, i.e., the carotenones without oxygen such as β-carotene and the xanthophylls with oxygen such as neoxanthin, violaxanthin (V), and lutein. The light-sensitive albino cultivars have the highest level of V among the tested cultivars. However, the level of β-carotene in light-sensitive albino cultivars was much lower than those in normal cultivar Fudingdabai and temperature-sensitive albino tea cultivar Baiye-1. Carotenoids, including carotenones and xanthophylls, are a group of pigments in plant that protect photosynthetic organisms from damages induced by free radicals such as reactive oxygen species originating from water splitting, the first step of photosynthesis (Zakar et al., 2016). Also, carotenoids are indispensable for the function of the photosynthetic apparatus, and particularly in that of photosystem II (PS) because of their high harvesting and photoprotective capacity (Sozer et al., 2010; Stamatakis et al., 2014). Carotenoids can provide more efficient light absorption under low light conditions (Koyama et al., 1996). However, excessive energy needs to be reduced to avoid photo-inhibition damage to the photosystems under high-light conditions (Powles, 1984). Carotenoids function to dissipate excessive energy or excitation nondestructively as heat, a phenomenon being called nonphotochemical quenching (NPQ) of chlorophyll a fluorescence (Leonelli et al., 2017). Plants with light-induced zeaxanthin (Z) establish larger NPQ and Z formation shapes the photosynthetic membrane into a responsive state against high-light conditions (Powles, 1984). The NPQ mechanism involves the conversion of V into Z. The interconversion of violaxanthin (V), antheraxanthin (A), and zeaxanthin (Z) (VAZ-cycle) plays an important role in NPQ. During
exposure to excessive light, the enzyme viola-
lanthoxanthin deepoxidase (VDE) is activated 
and converts V to Z via the intermediate A 
(Yamamoto et al., 1999). In limiting light 
(or darkness), zeaxanthin epoxidase (ZEP) regen-
erates V through the addition of epoxy groups 
to the β-ionone rings of Z and A (Hieber et al., 
2000). The high level of V in light-sensitive 
cultivars (Table 1) might be interesting for 
their stress responses to high light. It was 
reported that a high light-inducible protein 
Synechocystis HliD binds chlorophyll a and 
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The concentrations of neoxanthin and 
lutein in the light-sensitive albino tea culti-
vars lie between normal cultivar Fudingdabai 
and temperature-sensitive albino cultivar 
Baiye-1. β-carotene is essential for the assem-
bly of PS II and PS I trimer, whereas xantho-
phyls including V can stabilize them (Zakar 
et al., 2016). Low level of β-carotene in the 
light-sensitive cultivars is considered to be 
related to their low level of chlorophyll a, and 
it might be an important factor leading to their 
light sensitivity.

The concentrations of neoxanthin and 
lutein in the light-sensitive albino tea culti-
vars lie between normal cultivar Fudingdabai 
and temperature-sensitive albino cultivar 
Baiye-1 (Table 1). Normally, the leaves of 
light-sensitive albino tea are in yellow color 
but those of temperature-sensitive albino tea 
are in white color (Fig. 1). The high levels of 
V, lutein, and neoxanthin are considered to be 
responsible for the yellow color of the light-
sensitive albino tea leaves after being 
unmasked by the disappearance of chloro-
phyls.

Morphological Characteristics

Table 2 shows the major trait characters of light-sensitive and temperature-sensitive 
albino cultivars. The leaves on the tender 
shoots of light-sensitive albino tea plants 
are always in yellow color owing to lack of 
chlorophylls and abundance of xanthophylls 
such as lutein, V, and neoxanthin. However, 
the mature leaves under the shield of canopy 
are in green color and they are the major 
contributors to the photosynthesis. The yel-
low leaf will become green after it is covered 
by a piece of paper for 1 week (Fig. 2) (Li 
et al., 2008), suggesting that the albino leaves 
in yellow color are induced by sunlight and 
the albino phenotype is reversible by sun-
shine. Because the leaves are sensitive to 
light, the young plants are easily injured in 
strong sunshine (Fig. 3A). The young plants 
with albino tender leaves but few mature 
green leaves are prone to be damaged by hot 
sunlight in the summer, resulting in low 
survival rate at the early stage after trans-
plantation. In this case, the farmers are 
advised to shield their young tea plants using 
sunshade nets with 30% to 50% light trans-
mittance in the first summer after transplant-
ing (Fig. 3B) (Wang et al., 2008).

Hypoplasia of chloroplast development is 
found to be an important factor leading to 
the lack of chlorophylls and leaf albino pheno-
type. Under transmittance electronic micros-
copy, abnormal chloroplasts were observed 
in the light-induced albino leaves, showing 
less grana stacking and thylakoids. However, 
the grana stacking and thylakoids were 
enriched when the albino leaves were shielded 
by sunshade nets. These suggest that inten-
sive sunlight induces the hypoplasia of chlo-
rophylls by suppressing the development of 
thylakoids and grana in the albino tea cultivar 
(Li et al., 2016b).

Molecular Genetic Mechanism

Molecular genetic studies show that the 
expression patterns of genes in light-sensitive 
albino tea plants involving in the metabolic 
pathways relating to chlorophylls and carot-
enoids are different from those in normal tea 
plants. Geranylgeranyl-PP is a product of 2-
C-methyl-D-erythritol-4-phosphate (MEP) 
pathway, and it is the precursor of carotenoids 
synthesized in carotenoid pathway and also 
the precursor of chlorophyll biosynthesized in 
chlorophyll pathway (Fig. 4). Compared with 
the normal tea cultivar Fudingdabai, the expres-
sion of the 1-deoxy-D-xylulose-5-phosphate syn-
thases (DXSs, including DXS1, DXS2, and 
DXS3), a key enzyme in the MEP pathway, 
and also the gene magnesium chelatase subunit 
D (CHLD) in the chlorophyll pathway are 
downregulated by strong sunshine and upregu-
lated by sunshade in the light-sensitive albino 
teab plants. However, the transcription of some 
genes involving in the carotenoid pathway such 
as phytoene synthase (PSY), phytoene desa-
turase (PDS), ζ-carotene desaturase (ZDS), 
lycopene ε-cyclo-(LCYE), lycopene β-cyclo-
ne (LCYB), carotene ε-monoxygenase (LUT1), 
ZEP, and VDE, are upregulated by strong 
sunshine in the light-sensitive albino tea plants 
(Li et al., 2016b). The expression pattern of the 
genes involving in the carotenoid pathway and 
chlorophyll pathway are consistent with the 
accumulations of chlorophylls and carotenoids 
in Table 1.

Digital gene expression profiling and 
quantitative real-time PCR (qRT-PCR) stud-
ies show that intensive light inhibits the 
expression of PsbII 10-kDa protein (PsbR) 
in light-sensitive albino tea cultivar Baiji-
guan, resulting in the reduction of chloro-
phyll biosynthesis and the less stability of PS 
II and chloroplast (Wu et al., 2016). The 
expressions of chloroplast genes PsbB, PsbA, 
PsaE, PsaF, PetA, and light-harvesting com-
plex (LHC) chlorophyll a/b binding protein 
(Lhca 4) are downregulated in the light-
sensitive albino tea cultivar Zhejianguang-1, 
compared with those in normal tea cultivar 
Longjing-43 (Wang et al., 2016). These 
genes are important for photosynthesis and 
growth of tea plants and their suppression by 
high light also explains why the survival rate

| Cultivars      | Yujinxianga | Huang-29 | Huang-89 | Huang-139 | Baiye-19 | Fudingdabai9 |
|---------------|-------------|----------|----------|-----------|----------|-------------|
| Total amino acids (mg·g⁻¹) | 56.85 ± 1.09 | 76.63 ± 3.83 | 73.37 ± 1.67 | 73.72 ± 3.13 | 64.52 ± 1.48 | 46.25 ± 0.44 |
| Total catechins (mg·g⁻¹) | 175.83 ± 1.07 | 128.68 ± 0.69 | 141.31 ± 1.58 | 133.60 ± 0.82 | 196.80 ± 6.83 | 188.88 ± 2.58 |
| Caffeine (mg·g⁻¹) | 39.71 ± 0.25 | 30.14 ± 0.57 | 28.18 ± 0.22 | 32.86 ± 0.25 | 28.40 ± 0.78 | 34.27 ± 0.39 |
| Chlorophyll a (µg·g⁻¹) | 134.51 ± 11.32 | 31.53 ± 6.94 | 76.06 ± 25.26 | 61.91 ± 7.64 | 282.04 ± 16.80 | 762.98 ± 46.28 |
| Chlorophyll b (µg·g⁻¹) | 449.41 ± 79.69 | 206.60 ± 64.16 | 306.78 ± 17.82 | 311.45 ± 21.87 | 639.94 ± 25.38 | 1,325.05 ± 308.29 |
| β-carotene (µg·g⁻¹) | 158.72 ± 12.19 | 100.88 ± 14.10 | 112.99 ± 6.31 | 114.53 ± 18.11 | 146.20 ± 7.35 | 379.19 ± 4.96 |
| Neoxanthin (µg·g⁻¹) | 78.09 ± 8.22 | 65.70 ± 1.61 | 65.86 ± 3.96 | 56.51 ± 2.43 | 69.92 ± 0.56 | 127.51 ± 28.76 |
| Violaxanthin (µg·g⁻¹) | 45.40 ± 6.71 | 53.64 ± 0.35 | 52.09 ± 4.27 | 63.43 ± 2.70 | 26.72 ± 0.00 | 31.63 ± 1.51 |
| Lutein (µg·g⁻¹) | 201.37 ± 6.73 | 174.70 ± 0.55 | 189.06 ± 18.63 | 221.31 ± 1.21 | 156.79 ± 15.12 | 373.77 ± 22.27 |
| References | Li et al. (2016c) | Li et al. (2016b) | Li et al. (2016b) | Li et al. (2016b) | Li et al. (2016b) | Li et al. (2016c) |

9Shoots with two leaves and a bud were tested.
1Light-sensitive albino tea cultivars.
2Temperature-sensitive albino tea cultivar and its former name was White leaf No. 1.
3Normal tea cultivar with green leaves.

Fig. 1. Comparison of light-sensitive and temperature-sensitive albino tea leaves. Left: light-sensitive albino tea cultivar; Middle: temperature-sensitive albino tea cultivar; Right: normal cultivar.
of the transplanted young plants was low at the early stage after transplantation. The expressions of genes involving in tea polyphenols biosynthesis in light-sensitive albino tea cultivars show different patterns from those in normal tea cultivars. Chalcone synthase (CHS) is the entry enzyme in flavonoid biosynthesis and it is a key enzyme in the catechins biosynthesis during the phenylpropanoid pathway (Mamati et al., 2006). Anthocyanidin reductase (ANR), an ANR, is the enzyme catalyzing the synthesis of anthocyanidin from flavan-3-ol in the presence of NAD+, and NADP+ (Xie et al., 2003). Flavonol synthase (FLS) participates in flavonoid biosynthesis, in which it catalyzes the transformation of dihydroflavonol and 2-oxoglutarate into a flavonol and succinate in the presence of oxygen (Wellmann et al., 2002). In normal tea cultivars, these genes are upregulated under strong sunshine conditions in summer (Liang et al., 1996). However, the expressions of CHS, ANR, and FLS in the light-sensitive albino tea cultivar Zhonghuang-1 are suppressed by strong sunlight, compared with normal cultivar Longjing-43 (Wang et al., 2016). This is the reason why the albino tea cultivars have less polyphenols than the normal tea cultivars. Heat shock proteins (HSPs) are a family of proteins that are produced by cells in response to exposure to stressful conditions such as heat, cold, and ultraviolet light (Ritossa, 1962). Many members of HSPs perform chaperone function by stabilizing new proteins to ensure correct folding or by helping to refold proteins that were damaged by the cell stress (De Maio, 1999). The dramatic upregulation of the HSPs is a key part of the heat shock response and is induced primarily by a heat shock factor (Wu, 1995). Various HSPs were shown to be differentially expressed in the leaf and root of drought-tolerant and drought-sensitive plants in response to drought. Upregulation of the HSPs is used to confer stress tolerance to hybridized plants, hoping to address drought and poor soil conditions for farming (Vinocur and Altman, 2005). Therefore, the downregulation of the HSPs HSP70 and HSP90 in cultivar Huangjinya under strong sunshine conditions is considered to be related to its light-sensitive albino properties (Song et al., 2017).

**Conclusion**

Both light-sensitive and temperature-sensitive albino tea cultivars contain high concentrations of amino acids and low levels of chlorophylls, and also the former contains less catechins than the latter. Because of expression upregulation of genes involving in carotenoid pathway including PSY, PDS, ZDS, LCYE, LCBY, LUT1, ZEP, and VDE, the light-sensitive albino tea cultivars contain higher levels of xanthophylls such as lutein, V, and neoxanthin than the temperature-sensitive albino tea cultivar, resulting in yellow color of their leaves, whereas white color of the latter leaves. Hypoplasia of chloroplast development and expression downregulation of genes involving in chlorophylls biosynthesis are responsible for the
albino leaf growth. In light-sensitive albino tea cultivars, the expressions of chloroplast genes PsbB, PsbA, PsaE, PsAF, PetA, LHC, and Lhca 4 are downregulated, resulting in the hypoplasia of chloroplast development, showing less grana stacking and thylakoids. The expression downregulation of genes involving in the MEP pathway, such as DXS, and genes involving in chlorophyll pathway, such as CHLH, are important factors leading to the lack of chlorophylls. The expression downregulation of genes involving in tea polyphenols biosynthesis, such as CHS, ANR, and FLS are leading factors for the reduction of catechins in the light-sensitive albino tea cultivars.

However, how the amino acids are highly accumulated in the light-sensitive albino tea leaves has not been understood so far. It is of great importance to clarify the mechanism of amino acid accumulation in the light-sensitive albino tea cultivars in the further studies.

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