PHOTOVOLTAIC TEA PLANTATION IN CHINA
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Abstract
Photovoltaic (PV) agriculture is a new type of agriculture that widely applies solar power generation to modern agricultural planting, breeding, irrigation, pest control and power supply of agricultural machinery. PV-agriculture system meets the requirements of biological chain relationship and biologically optimal production of raw material-energy system, follows the production rules of agricultural products and innovates material and energy conversion technology so as to achieve the purpose of intelligent light, water and temperature regulation. The agricultural products produced by PV-agriculture system is safer, more nutritious and more productive than the products produced by the traditional way. Tea (Camellia sinensis) is a typical weak light tolerant plant and the best crop for building PV-agriculture system. The advances in PV-tea plantation system studies, including effects of PV on yield, quality, abiotic stress and economic efficiency of tea production are discussed in the present paper.

Keywords: Camellia sinensis, tea yield, tea quality, abiotic stress, economic efficiency

1. INTRODUCTION
With the accelerated process of economy, environmental issues and energy issues have become the focus of attention of world, along with the energy crisis and environmental pollution. As a result of the environmental protection consciousness enhancing, many countries starts to advocate the sustainable development, encourage investment in the development of environment-friendly product and expanding the clean energy generation.

Solar energy is one of the most important renewable energy, has long been the attention of people. The photovoltaic(PV) is developing rapidly in China. Apart from market demand, it is mostly due to the strong policy for PV energy incentivisation, for example, “The Twelfth Five-Year Plan of PV Industry”, in which PV power generation is promoted with subsidies, with combination of rural poverty alleviation not only were in [1]. Due to the policy encouragement. The capacity of installed PV in China have shown a rapid increase in the last few years (Figure 1). The total capacity of installed PV in China in 2018 was increased to 174 GW, up 34% from the previous year (National Energy Administration (NEA). Statistics of photovoltaic power generation in 2018. http://www.nea.gov.cn/2019-03/19/c_1379707428.htm). However, the PV panels have potential conflicts of interest between daylighting and energy efficient. The desertification of land where solar panels are deployed is one of the major problems in the PV industry.
The agricultural land is usually cheap compared to other land-use destinations, pulling the investors to looking for agricultural lands for PV power plants and speculate on the public incentives [2]. PV system linked to agriculture such as PV agricultural greenhouse [3-5], PV pumps [6-8], or open fields with PV arrays installed above the crops, is a trend setting area which can integrate energy and food production on the same land unit [9, 10]. At the same time, the electricity demand of different agricultural activities can be met by harnessing the solar energy [11]. However, the installation of PV panels reduces solar radiation that falls to the plants inside the PV system, this aspect posed the problems of the competition between land uses for energy towards crop production. Given the lack of knowledge and agricultural experience, these new PV farms preferred to concentrate on the PV energy production and did not invest in the agricultural infrastructures for efficient cultivation [3].

Due to the high cost of solar energy PV power and the short sunshine duration under the solar panels, it is better to plant crops with high economic income and weak light tolerance to suit for the microclimate under the PV system. Only with a suitable planting species and planting pattern with the appropriate scale investment in PV-agriculture system can achieve double wins of crop economy and electricity generation benefits.

Tea plant (*Camellia sinensis* L.) belongs to the Theaceae family and is a popular nonalcoholic healthy beverage that is consumed in all regions of the world, with many health benefits [12]. Tea plants are adapted to the understorey of forests in their native habitat. There is evidence showing that photosynthesis of tea leaves is decreased under strong solar radiation conditions at noon, particularly in dry seasons. It is considered that the decrease of photosynthetic active radiation (PAR) falling tea plant to canopy caused by PV panels might prevente midday depression of photosynthesis and benefit the tea production [13, 14]. Furthermore, the quality of manufactured tea was improved under shading treatment in the summer [15]. The effects of PV arrays on yield and quality of tea were investigated in the present paper.

2. THE EFFECTS OF PV ON CROP PRODUCTION

The PV installations often occupy large areas of land, since they are specifically built for PV energy massive production, resulting in an ecological impact on the agricultural ecosystems such as air temperature, relative humidity, and solar radiation. These factors are important for the actively growing crops and could influence crop yield and quality in various ways. Typically, greenhouses catch about two thirds of the available solar radiation and their efficiency is strongly related to their position and geometry [16], this efficiency further decreases due to the PV panels on the roof [17]. The researchers
observed that the solar radiation inside the greenhouses embedded PV panels is 213.73kWhm\(^2\) for a duration of 85 days of the experiment, being lower than that inside the the greenhouse without PV panels which is 238.04 kWhm\(^2\), because of PV shading [17]. The shading of the photovoltaic panels on the underlying tea plants changes over time throughout the day, and the shading degrees depend on the structures of the PV penels, which are 24\%–42.5\% and 33\%–49\%, under the checkerboard fixed PV system (Figure 2, A) and horizontal single-axis tracker PV system (Figure 2, B) respectively [18].

![Fig. 2. Checkerboard fixed PV system (A) and horizontal single-axis tracker PV system (B)](image)

Yano et al. [19] investigated the spatial distribution of sunlight energy in a greenhouse equipped with a large PV array of 12.9% shading rate, and it showed that the radiation received by plant differentiated between straight-line arrangement and checkerboard arrangement PV array, being 81\% and 77\% compared with the control greenhouse, respectively. The available solar radiation inside PV system changed with the design parameters such as PV covering rate, height and orientation of PV panels, checkerboard pattern, and etc. The yearly global radiation decreased averagely by 0.8\% for each additional 1.0\% PV cover rate and increased by 3.8\% for each additional meter of greenhouse height [20]. There are several types of semi-transparent PV modules that could be used as covering material of plants [21, 22], but their efficiencies per covered roof surface area are low and therefore cost effective systems of opaque PV panels of higher efficiency have a greater price/ performance ratio.

Agriculture performance in most cases is negatively affected by shade, including slowing down growth, reducing total biomass production at maturity, and leaf characteristics [2, 23-26]. In Germany, 57\% and 34\% reduction in the photosynthetic photon flux density (PPFD) integral over the growing period caused a decrease of the tomato dry weight of 31\% and 19\% [27]. In Japan, the accumulation of fresh and dry-weight on welsh onion cultivated under a 12.9\% PV roof coverage reduced significantly [28]. In Spain, the marketable production of tomatoes did not appreciably affected inside a PV greenhouse with 9.8\% PV cover ratio, but it influenced the fruit size, color and maturation [29]. In southern France, the yield of lettuce grown in an agriculture-PV system with 50\% PV shade, ranged from 81\% to 99\% of the control, due to the enhancement of radiation interception efficiency, achieved by increasing the leaf area [26]. In Malaysia, Java Tea, a kind of herbal crop, collected final raw material with a reduction of 73.7\% under PV array [30].

All these influences of PV on crops provide information on selecting crop species suitable for the weak solar light conditions inside PV system and achieving the optimal balance between agricultural income and energy production.

3. THE EFFECTS OF SHADE ON TEA PLANTS

In tea plantation, shading is one of the traditional agricultural practices to improve tea quality through modifying the structural traits, photosynthesis, color, and chemical compositions in tea leaves.
3.1 Photosynthesis of tea

Photosynthetic light compensation point (LCP), and light saturation point (LSP) of various tea cultivars vary with growing season, fertilization, irrigation and etc [31]. There were studies showing the LCP and LSP of some tea cultivars (Table 1). It shows that the radiation demanding for vigorous grow of most tea cultivar is less than 1200 μmol·m⁻²·s⁻¹. However, according to the research of climatology and statistics, the PFD of most tea-growing areas in China it is more than 1200μmol·m⁻²·s⁻¹, particularly in summer [32]. Tea is a weak light tolerant plant, and strong intensity of radiation will lead to photo-inhibition (PI), in which photosynthesis is inhibited [31], and hence shading is often a measure to improve yield and quality [33, 34]. The photosynthetic capacity of tea is inferred better for leaves grown under shading conditions than that in the unshaded open fields. The air temperature might be lower and the air moister increased under the lower radiation conditions, in which the tea grows well [14, 31, 35].

<table>
<thead>
<tr>
<th>Tea Cultivars</th>
<th>LCP (μmol·m⁻²·s⁻¹)</th>
<th>LSP (μmol·m⁻²·s⁻¹)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fudingdabai</td>
<td>35–56</td>
<td>382–750</td>
<td>[36-38]</td>
</tr>
<tr>
<td>Jinguang</td>
<td>46–164</td>
<td>240–243</td>
<td>[37, 38]</td>
</tr>
<tr>
<td>Huangjinya</td>
<td>36–188</td>
<td>256–329</td>
<td>[37, 38]</td>
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<tr>
<td>Yujinxiang</td>
<td>42</td>
<td>361</td>
<td>[37]</td>
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<tr>
<td>Baiyeyihao</td>
<td>84</td>
<td>452</td>
<td>[38]</td>
</tr>
<tr>
<td>Siningxueya</td>
<td>100</td>
<td>716</td>
<td>[38]</td>
</tr>
<tr>
<td>Zijuan</td>
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<td>392</td>
<td>[38]</td>
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<td>76</td>
<td>276</td>
<td>[38]</td>
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<tr>
<td>Longjing43</td>
<td>112</td>
<td>1000–1200</td>
<td>[39]</td>
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Table 1. Different cultivars of tea’s light compensation point, light saturation point

3.2 Pigments of tea

The shading cultivation by sunlight shielding using shading net affect tea quality through altering the pigments and chemical compositions. There was research showing that the shade treatment increased the amount of chlorophyll, which plays a role in light absorption in the chloroplast to maximize light absorption [15, 40]. Chlorophyll content is also closely related to the scores for the colour of dry tea and its tea infusions [41, 42]. For example, matcha is a very fine powder been ground by special green tea leaves picked from tea plants under 60-90% shade for about 7-10 days before harvesting. This shade treatment increased chlorophyll content in tea leaves, leading to darker green colour [43]. Although the mean contents of chlorophyll a and chlorophyll b were increased with increase in shading rate, the shading treatment had no effect on carotenoid content [40, 44]. Besides the green tea phenotypes, similar shade-induced response on pigments was detected from albino tea cultivars, pale yellow leaves in albino cultivars always have aberrant chloroplast development, but for the most part, could be recovered by shading treatment, in which the leaves regain green colour with increase in chlorophylls and carotenoid, and also the development of chloroplasts [45, 46].

In addition, the ratio of chlorophyll a to chlorophyll b in shadded tea leaves was lower than that in open culture [47]. The change in ratio of chlorophylls might be its adapted low light to maintain photosynthetic intensity [48, 49].

3.3 Chemical compositions of tea

The flavour of tea is principally depend on its chemical components. Artificial control of tea growing, i.e., typically shade treatments, can lead to significant changes of the tea metabolite compositions. Compared to the unshaded leaves, the contents of catechins and flavonols in shaded leaves decreased
by 53.37% and 43.26%, respectively [50]. The major catechins, including catechin (C), epicatechin (EC), gallatechin (GC) and (-)-epigallocatechin (EGC), decreased significantly in tea shoots throughout the whole shading period [51]. But the concentration of (-)-Epigallocatechin gallate (EGCG) in matcha made from these leaves is higher than that in green tea [52]. It is reported that catechins biosynthesis in tea shoots is predominantly regulated by UV through the UVR8-mediated signal transduction pathway to MYB12/MYB4 downstream effectors [51]. The expression of gene encoding phenylalanine ammonia lyase which catalyzes the biosynthesis of catechin derivatives precursors was down-regulated in tea plants grown under shaded conditions [50], resulting in reduction of catechins [53].

Generally, tea leaves grown under shaded conditions contain less catechin derivatives but is more rich in amino acids [15, 50, 53-56]. The levels of most amino acids were lifted as shading period extended, along with reductions of glucose level [54]. It is reported that most enzymes involved in biosynthesis of amino acids were down-accumulated and two chloroplasts proteases were upregulated under dark treatment conditions, suggesting that amino acid accumulation in dark-treated leaves was not due to activation of amino acid biosynthesis process, but contributed by the proteolysis of chloroplast protein [57].

Apart from catechins and amino acids, some other volatile and non-volatile metabolite profiles differed significantly between shading treatment and untreated leaves [53, 58]. The levels of volatiles, especially volatile phenylpropanoids/benzenoids (VPBs), significantly increased in the tea leaves grown in shading treatment for 3 weeks. Upstream metabolites of VPBs showed lower levels in shading treated than in control leaves, whereas the contents of most amino acids including L-phenylalanine, a key precursor of VPBs, were significantly enhanced [53].

On the whole, these studies indicate that the growth and quality of tea facilitated by shady condition.

4. CONCLUSIONS AND FUTURE EXPECTATIONS

Through above analysis, it is considered that the development of PV tea plantation is a best choice in tea industry. The major effect of PV system exposure to crops is on the sunlight, but to some extent this weakness can be turned into a strength by installing PV arrays above tea plants in open fields or greenhouses. The installation of PV panels reduces solar radiation that falls to the plants inside the PV-agriculture system [19], affecting their lighting and therefore crop growing [59]. However, there is evidence that photosynthesis of tea is decreased by strong solar radiation, in which partially shielding the sun light by PV system might benefit tea growing and tea production. In China’s Shandong Province, the fresh tea leaves yield in PV greenhouse was 130 kg/667m², being 62.5% higher than that in the regular greenhouse, and 117% over that in open field tea plantation, respectively [60]. The low productivity of tea may be related to inadequate assimilate production, as the rates of photosynthesis in tea plants in the regular greenhouse and open tea field are lower than that grow in PV greenhouse. Certainly the question of whether or not PV system is appropriate to maintain growth rates at high levels depends on so many factors such as solar radiation, temperature and humidity. It is difficult to generalize although it can be assumed that, increase of photosynthetic rate could be attributed to reduction of light intensity, as well as cooler temperatures and higher moisture induced by the decreased radiation by PV panels. Moreover, the PV tea plantation can decrease occurrence of pests and diseases, resulting in yield improvement. Investigations on diseases and insect pests on tea plants showed that tea in greenhouse imbeded with PV arrays had fewer and lower risk of pests and diseases than regular greenhouse and open tea field [60]. The exact mechanism under this phenomenon remains to be investigated.

PV system as a shade installation not only increased tea leaves yeild, but also improved the tea quality. According to the sensory evaluation and color measurement data, the shade treatment improves the nutritional and sensory quality of green tea and black tea [15, 61]. Amino acids, especially theanine, which have umami or brothy taste, contribute to the mellow taste of green tea, whereas catechins, caffeine and flavonoids with bitter taste contribute to the astringency. Shade treatment in summer tea plants decreased the intensities of astringency and bitterness of tea [15], which was considered to be related to the increase in compounds with umami and sweet taste, such as theanine, accompanying with
A decrease in catechins [43, 54, 62]. These studies delineates the possibility to produce green teas with high umami taste and less bitter taste in PV tea plantation.

Although tea plant has a potential of low-light-tolerance, the optimum shading rate varies with tea cultivars. The response of various tea cultivars to low-light conditions induced by PV panel system and the changes in photosynthetic characteristics and chemical compositions of tea leaves remain to be further investigated and improved.

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REFERENCES


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