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Winter Wheat (*Triticum aestivum* L.) Grain Yield, Quality, and Net Photosynthesis When Grown Under Semi-Transparent Cadmium Telluride Photovoltaic Modules Near Maturity

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Abstract. Semi-transparent cadmium telluride (ST-CdTe) photovoltaic (PV) technology is based on the use of CdTe in a thin film (2-8µm) to absorb and convert sunlight into electricity. The thin film is deposited onto clear glass and can be custom abraded to produce ST-CdTe PV modules of a desired transparency level (e.g. 50% full sun/50% transparency) making it an intriguing option for agrivoltaics (AV) applications. Recent improvements in ST-CdTe PV technology have matched the efficiency of crystalline silicon (c-Si) PV with the levelized cost of energy production far lower than conventional gas, coal, and nuclear generation [1]. A field experiment was conducted whereby ST-CdTe PV modules of two transparency levels (20% and 50%) and a full sun control (100% transparency) were temporarily installed in a RCBD with three replicates over winter wheat (*Triticum aestivum* L.) plants after anthesis and until harvest. The average net photosynthetic rate (Pn) of the full sun control was significantly higher than the 20% ST-CdTe PV module, but not different from the 50% transparency module. Measured factors for yield and protein content were statistically insignificant, except for wheat head number, which was significantly higher under 50% ST-CdTe PV than both the 20% ST-CdTe and full sun control. These results provide evidence that ST-CdTe PV module technology can provide renewable energy while balancing wheat yield potential and grain quality. The ability to adjust the transparency levels of the modules make ST-CdTe another PV technology option to consider for AV applications.

Keywords: Agrivoltaics, CdTe, Wheat

1. Introduction

The commitment to reach net-zero carbon emissions has been accepted in many countries around the world, including the United States. According to the recent climate change report of the Intergovernmental Panel on Climate Change (IPCC), solar PV is, among all decarbonization technologies, the most efficient and most affordable way to decarbonize our energy system [2]. Solar PV prices have dropped dramatically over the last five years and now cost less than other power-generation technologies. In the US, subsidy-free power is now produced at the utility scale below 30USD/Megawatt hour (MWh) [2].

Interest in AV, the co-location of agriculture and PV, has increased considerably in the past several years due to an increased commitment to renewable energy generation paired with dwindling availability of new residential and commercial solar development sites. Farms are the next logical place to position new PV systems, but there are questions about how solar can be integrated into farming operations and cropping systems. Renewable energy development on existing farms is not a new idea as we have seen wind generating capacity increase dramatically from 21.6 Megawatts in 2000 to 4,692 Megawatts in 2020 [3]. AV is emerging as an attractive option to consider when expanding the on-farm energy generation portfolio and the opportunity for a dual-purpose land use model. Solar panels mounted over vegetation demonstrate significant surface temperature drops compared to arrays mounted over bare ground [4]. As modules experience efficiency losses above 25 °C, solar conversion efficiency is greater when solar PV is mounted over vegetation compared to exposed soil or gravel [5]. While both farmers and solar developers are interested in the co-location of agriculture and PV, the field is still relatively young in the U.S. and the body of research and science-based information is still too small to effectively aid in decision making processes.

One question facing growers and solar developers when considering AV is solar module (i.e. panel) choice, and there are more technological options on the market now than were previously available. For example, traditional c-Si modules are widely available and relatively inexpensive but are almost completely opaque (0% transparent). Bifacial c-Si modules are also widely available, are moderately priced, generate electricity on both the surfaces of the modules, and are about 5% transparent. CdTe PV modules are new on the U.S. market and more challenging to source. This thin film PV technology requires 100x less material to manufacture as compared to c-Si and recent improvements in manufacturing techniques along with energy production efficiencies have made CdTe PV cost effective in large scale installations [6]. ST-CdTe PV modules can be customized during manufacturing to allow more or less light penetration and subsequently allow for more or less light for crop growth. The ability for ST-CdTe PV to have tailored transparency levels make this technology intriguing for AV applications. Each of these module types will influence the cost of an AV installation, return on investment, electricity generation, crop microenvironment, soil moisture, and social acceptance. Growers, the general public, and solar developers need to understand these interactions and trade-offs when designing systems that are truly integrated.

Another consideration for growers when considering AV is crop selection. The shadow effect from the high coverage of opaque c-Si PV panels has been shown to have negative impacts on plants under certain circumstances [7, 8]. However, the literature is growing around crop production in AV systems [9, 10]. An increasing number of crop species have been evaluated in AV systems and even shade intolerant crops such as corn have shown to have increased biomass when the solar modules were placed at a low density [11].

Colorado is the fifth largest winter wheat producing state in the USA with 1.9 million acres harvested in 2021 and value of production of $466 million USD [12]. Wheat represents a largely dryland crop with very large acreages in the state and is of economic importance to the rural economies of eastern Colorado. It is an important rotational crop representing a large number of acres and therefore offers more choice of location for AV site selection. To date we are not aware of any research involving solar modules of varying transparency and agronomic crops of economic importance to Colorado. Furthermore, a recent (2021) critical literature review of AV systems noted that research on varying transparency modules has been limited to use in greenhouse applications [13].

2. Experimental Methodology

A crop of hard red winter wheat (*Triticum aestivum* L.) cv. Brawl CL Plus was established for seed production at Colorado State University's Agricultural Research, Development, and Education Center-South (ARDEC-S) in Fort Collins, CO USA. On 15 Sep 2022, winter wheat was seeded at 45kg/ha in twin rows on beds spaced 76cm apart. Wheat plants grew vegetatively through the fall of 2022, vernalized over the winter months, and continued their life cycle in the spring of 2023. On 1 July 2023, after wheat anthesis and the final irrigation of the crop, ST-CdTe PV modules of two transparency levels (20% and 50%), and a full sun control (100%

transparency) were temporarily installed over wheat plants in a randomized complete block design (RCBD) with three replicates. The ST-CdTe modules remained in place until harvest (Figure 1). The wheat crop was flood irrigated throughout the growing season and did not experience drought stress. Single modules were secured 20cm above the crop at the bottom edge, and tilted 30^{o} south. The modules were custom abraded (Toledo Solar, Toledo Ohio USA) with opaque Cd-Te striped rectangular bands across the width of the panels that allowed for either 20% or 50% sunlight transmission. Modules with 20% transparency had 2mm Cd-Te bands alternating with 0.67mm clear glass and the 50% transparent modules had 1.43mm Cd-Te bands alternating with 1.43mm clear glass. Gas exchange of the flag leaf was measured using a Licor-6400 portable photosynthesis system (LICOR, Lincoln NE USA) between 08:00 and 11:30AM on 13 July 2023. Net photosynthetic rate (Pn) was calculated based on flag leaf area.

On 31 July 2023, 0.42m^2 plots of wheat were hand harvested from the area below the ST-CdTe PV modules. Total biomass, head weight, head number, straw weight, and grain yield data were collected. Grain protein content was estimated using near-infrared (NIR) spectroscopy on a 14% moisture basis.

Figure 1. *ST-CdTe PV modules of two transparency levels (20% and 50%) and a full sun control over a winter wheat crop grown at Colorado State University's ARDEC-S facility.*

3. Results and Discussion

Statistical analysis was conducted using R version 4.2.3. and data were subjected to analyses of variance (ANOVA). Means separation was based on Fisher's Protected LSD. As expected, the net photosynthetic rate (Pn) of the full sun control treatment was significantly higher than the 20% ST-CdTe PV module. However, the 50% ST-CdTe PV module was found to have a statistically equivalent Pn as the full sun control. Grain quality, represented by protein content estimated with Near Infrared (NIR) spectrophotometry, was statistically equivalent for all treatments (Table 1).

Table 1. *Net photosynthetic rate and protein content of wheat grown under ST-CdTe PV.*

PV Module Type	**Net Photosynthetic Rate (umol/m2/s)**	**Wheat Grain Protein Content (%)**
ST-CdTe - 20 % Transparency	3.9 a*	13.2
ST-CdTe – 50 % Transparency	7.8 ab	13.3
Full Sun Control 100 % Transparency	11.8 b	13.5
P-value	**0.0081**	**0.8693**

Means of measured yield factors including total biomass, head weight, and straw weight were not significantly different among transparency levels in this experiment. Interestingly, the average number of wheat heads harvested was significantly higher under the 50% transparency ST-CdTe PV module than both the 20% transparency and full sun control treatments (Figure 2). Furthermore, a clear numerical trend for all measurements of wheat yield illustrates that the 50% ST-CdTe PV was the highest followed by the full sun control, and the 20% ST-CdTe PV treatment was the lowest (Figure 2).

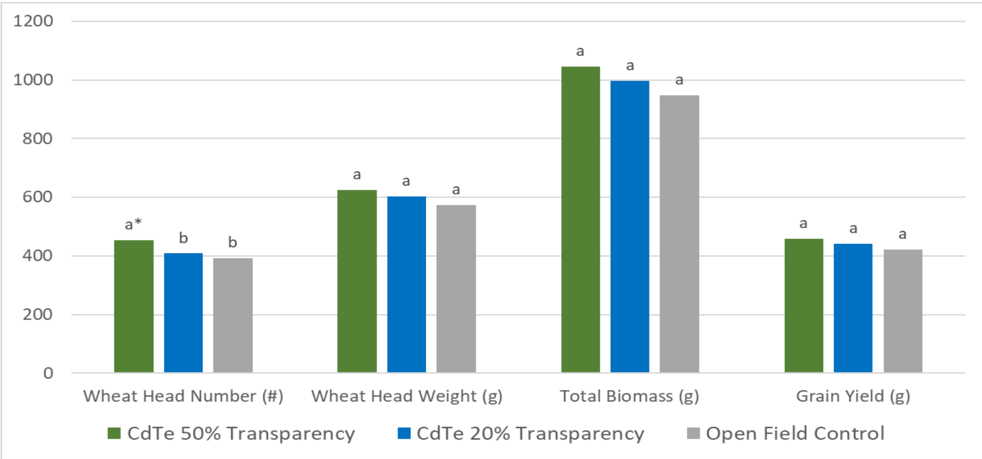

Figure 2. *Winter wheat yield when grown under ST-CdTe PV modules.*

These results are based on a single year (2023) of data collection. A similar trend in Pn from this study was observed on wheat in China where Pn was significantly reduced with 90% and 50% late-season shading (10% and 50% transparency, respectively) compared to the full sun control [14]. Another study [15] found that at 67% and 35% of full sunshine, wheat Pn and yield decreased significantly as compared to the full sun control. Interestingly, grain yield and protein content were largely unaffected by the shading of the ST-CdTe PV modules evaluated in this experiment. Additional work is needed to determine the most efficient transparency level of ST-CdTe PV modules for AV applications. Future research could also include modules installed earlier in the wheat growth cycle. Further, more research is needed that directly compares ST-CdTe modules to bifacial and c-Si modules both in terms of crop impacts but also social acceptance. Nevertheless, these results provide evidence that ST-CdTe PV module technology can provide renewable energy while balancing crop yield potential, grain quality, and photosynthesis.

Data availability statement

Data supporting the results of this manuscript can be accessed in the FAIR-aligned public repository, FAIRDOMHub. Doi: https://doi.org/10.15490/FAIRDOMHUB.1.DATAFILE.7319.1

Author contributions

The authors' contributions are as follows: JD was responsible for data curation, formal analysis, visualization, and writing the original draft. DK was involved in investigation and writing review and editing. MEU was responsible for conceptualization, funding acquisition, methodology, project administration, supervision, and validation.

Competing interests

The authors declare that they have no competing interests.

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