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IMPACTS OF ROOF–MOUNTED PHOTOVOLTAIC PANEL SHADING AND SOIL MULCHES ON GREENHOUSE ENERGY USE AND CUCUMBER YIELD

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ABSTRACT

Greenhouse farming has become an increasingly vital component of modern agriculture, providing a controlled environment that supports crops year-round. A field experiment was conducted to test the effect of shading photovoltaic panels and covering the soil with polyethylene on indoor air temperature and relative humidity. The experiment examined the impact of shading on cucumber production during the autumn and spring seasons of 2024-2025 in the Talkaif district of Nineveh Governorate, North Iraq. Statistical analysis was adopted to analyse the experimental data. Fully mulching substantially reduces soil evaporation, and, combined with shading, helps reduce temperature variations inside the greenhouse. The temperature variations in the shaded greenhouse, with black mulch for the soil in both seasons, ranged from 5.9 to 11 ºC. The temperature variations in the shaded greenhouse, which used white mulch, ranged from 6.2 to 13.9 °C in both seasons. The shading with photovoltaic panels of both types and the mulching colors achieved a surplus in cucumber crop yield in the autumn season compared to the conventional greenhouse, ranging from +20.56 to +42.12 g. plant^{-1}. Although there was no increase in cucumber crop yield in the spring, the yield was higher than in the autumn. When comparing the yield in the shaded greenhouse for the same spring season with the conventional greenhouse, the results ranged from -121.15 to +26.05 g.plant^{-1}. The increase in energy compensated for the decrease in cucumber crop yield, amounting to +112.74 kWh. Autumn season^{-1} and +116.98 kWh. Spring season^{-1}, respectively.

INTRODUCTION

The world is currently facing a significant problem related to global climate change and global warming, particularly in the Middle Eastern countries, including Iraq (Mohammed *et al.*, 2023). The Intergovernmental Panel on Climate Change (IPCC), in its Fourth Assessment Report, stated that preventing potentially catastrophic levels of climate change requires a 50% global reduction and an 80% reduction in industrialized countries by 2050, with a 100% global reduction achieved shortly thereafter (Komendantova *et al.*, 2011).

India and Africa are the original homes of cucumbers, where they have been cultivated for thousands of years. Cucumbers are also known for their nutritional and medicinal value (Zedan *et al.*, 2018). Growing cucumbers in greenhouses is one of the modern agricultural methods that provides a suitable environment for the plant, regardless of the agricultural season outside the greenhouse (AL-Habar *et al.*, 2013).

Greenhouse cultivation has become an increasingly vital component of modern agriculture, offering a controlled environment that extends growing seasons and enhances crop yield. However, greenhouses typically require substantial energy to maintain optimal internal conditions, particularly heating and cooling. This dependency on energy-intensive systems poses challenges to both sustainability and operational costs. In recent years, integrating renewable energy technologies, particularly photovoltaic (PV) panels, into greenhouse structures has emerged as a promising approach to reduce dependence on fossil fuels and improve energy autonomy (Hassanien *et al.*, 2016).

The concept of agrivoltaics, which refers to the dual use of land for crop cultivation and solar energy generation, has gained traction to optimize land use and reduce environmental impacts (Sarr *et al.*, 2023). When solar panels are installed on greenhouse roofs, they offer the dual benefits of power generation and partial shading. However, this shading modifies the internal microclimate by altering light penetration and thermal conditions. The extent and nature of these changes are dependent on the type, arrangement, and transparency of the installed PV panels (Gnayem *et al.*, 2024). Prior studies have shown that moderate shading from PV panels (approximately 25–40%) can have mixed effects on crop development, depending on seasonal light availability and crop-specific light requirements. For instance, certain shade levels have been associated with early flowering and improved photosynthetic efficiency in crops such as chili peppers in autumn (Hassanien *et al.*, 2022). Furthermore, the optical and thermal properties of flexible versus rigid PV modules differ, influencing the quantity of transmitted light and the distribution of shading patterns across the crop canopy.

In parallel, soil mulching is widely recognized as an effective agronomic practice that modifies the microclimate at the root zone. Mulch color significantly affects light reflectivity, soil temperature, and cucumber fruit production (Torres-Olivar *et al.*, 2016). Black polyethylene mulch absorbs solar radiation, raising soil temperature and promoting early plant development, particularly in cooler seasons. In contrast, white mulch reflects solar energy, reducing soil heat accumulation and potentially lowering daytime temperatures in warm environments (Marucci *et al.*, 2017). Despite its well-documented individual benefits, little research has examined how different mulching types interact with PV-induced shading in greenhouse environments.

Moreover, rigid and flexible PV modules are integrated into greenhouses, while flexible modules are often installed in greenhouses with curved roofs and walls. In addition to traditional opaque modules, some studies have reported the use of semi-transparent PV modules, which increase electricity generation by absorbing radiation reflected from the sky and ground, with slight shading effects (Gorjians *et al.*, 2021). A study by Khessro *et al.* (2022) showed that cucumber production inside greenhouses in Nineveh Governorate required a total energy input of 46,432 MJ ha⁻

^{1}, with a significant portion coming from electricity used to operate ventilation and environmental control systems. This makes electricity a key factor influencing the system's overall energy efficiency. The study also demonstrated that achieving a positive energy balance (energy output of 53,127 MJ ha^{-1}) is possible when inputs are managed optimally. These findings emphasize the importance of exploring alternative and stable energy sources that reduce dependence on the national grid, especially in areas experiencing power outages or high operating costs. Integrating photovoltaic solar systems into greenhouse design provides a clean and reliable electricity source, lowers long-term operating costs, and improves environmental sustainability, particularly by utilizing existing infrastructure and solar panels to shade the roof and enhance indoor climate.
Moreover, growing cucumbers under shaded greenhouses achieves more than twice the economic costs of the traditional method (Siwek and Lipowiecka, 2004). Operating costs and energy efficiency: Although immediate profitability is limited, the study predicts long-term financial sustainability through reduced operating costs and increased crop yields. The environmental benefits, including reduced greenhouse gas emissions and resource efficiency, align with broader sustainability goals (Nejatian *et al.*, 2024).

This study aims to elucidate their relative impacts on greenhouse performance and crop productivity by evaluating both panel types under the same environmental and cropping conditions. This research seeks to bridge the knowledge gap by investigating the effects of PV panel type (flexible vs. rigid) and soil mulch color (black vs. white) on the internal greenhouse environment and early cucumber yield throughout the growing season.

MATERIALS AND METHODS

Experimental Site and Crop

The experiment was conducted in three identical plastic greenhouses, each with a total area of 360 m^2 (40 m in length and 9 m in width), located in the Talkaif district of Nineveh Governorate, northern Iraq. The study aimed to investigate the effects of roof-mounted solar panel shading using both flexible and rigid photovoltaic (PV) panels, in combination with two soil-mulching colors, on the cost of producing cucumbers using photovoltaic energy compared with electricity from the national electricity grid. The test crop was cucumber (Cucumis sativus), cultivated with 900 cucumber seedlings in the Autumn of 2024 and repeated in the Spring of 2025.

Experimental Design

A combined design was applied with the type of solar panel (rigid or flexible) as the sub-factor and soil mulch color (black and white polyethylene) as the main factor. Furthermore, PV panels mounted on the roof structures of two non-climatized greenhouses were compared with a control greenhouse (no photovoltaic panels on the roof and no full mulching). Each treatment included three planting beds, each 10 m long and 0.8 m wide. A total of 25 cucumber plants were selected per bed, spaced evenly at 0.4 m.

Photovoltaic Panel Installation

- **Flexible PV panels**: five solar panels with 136 W electrical power rating for each, with a total area of 10.1 $m^{2,}$ were installed over the front portion of the greenhouse roofs. The panels were mounted with 40 cm spacing between each other, as shown in Figure 1.
- **Rigid PV panels**: Fifteen rigid solar panels with 120 W electrical power rating for each, with a total area of 9.72 m^2 were grouped into five sets and mounted on metal frames. Each group of three panels was fixed to the greenhouses' roofs in alternating orientations to optimize shading distribution, as shown in Figure 1.

Figure (1): Installation of flexible and rigid PV panels on greenhouses roofs

Soil Mulch Application

Black-and-white polyethylene mulch (90-micron thickness) was used as soil cover. The mulch was perforated at 40 cm intervals using a thermal punching tool to accommodate cucumber seedlings, as shown in Figure 2.

a B

Figure (2): Soil mulch application: a: white polyethylene mulch, b: black polyethylene mulch

Measured indicators

To evaluate the effects of shading and mulching, the following four parameters were measured throughout the growing season:

Solar radiation: Solar radiation recorded inside and outside the greenhouses using the VBR-100Plus PAR-Meter device; see figure (3). The device measures (PAR) photosynthetic active radiation (μmol.m^{-2}.s^{-1}) and transmits the data via Bluetooth to a mobile device using the VSensor App. These measurements enabled the quantification of radiation reduction due to PV panel shading during the experimental periods. The amount of external PAR in the autumn season averaged 951.93 μmol.m^{-2}.s^{-1}, while in the spring season averaged 1045.94 μmol.m^{-2}.s^{-1}. In addition, daily global solar radiation data for the experimental location were obtained from the Meteoblue database. These model-based data, expressed as global horizontal irradiance (kWh·m^{-2}·day^{-1}), were used to verify seasonal radiation trends and fill gaps when field measurements were unavailable. Differences between Meteoblue estimates and field measurements were expected due to differences in measurement type (PAR versus total global radiation), spatial averaging, and atmospheric conditions (e.g., localized dust or cloud cover). Therefore, the locally measured PAR data were considered primary for microclimate analysis, while Meteoblue data served as a supplementary reference for overall solar radiation assessment.

Figure (3): VBR-100Plus PAR-Meter from VABIRA [Source]

Temperature and Humidity of Shaded House: The temperature (°C) and humidity (%) were measured in shaded houses with PV panels and in the traditional house. The humidity level inside the greenhouse was calculated using a same devices from Govee (smart thermo-hygrometer) which shown in figure (4) with the following specifications: Accuracy: (temperature 0.3 °C, Humidity 3%RH), working temperature (-20 °C - 60 °C), and working humidity (0%RH-99%RH), connected to mobile with Bluetooth to export collected data, and they used to determine the effect of temperature and humidity on the produced energy and crop yield.

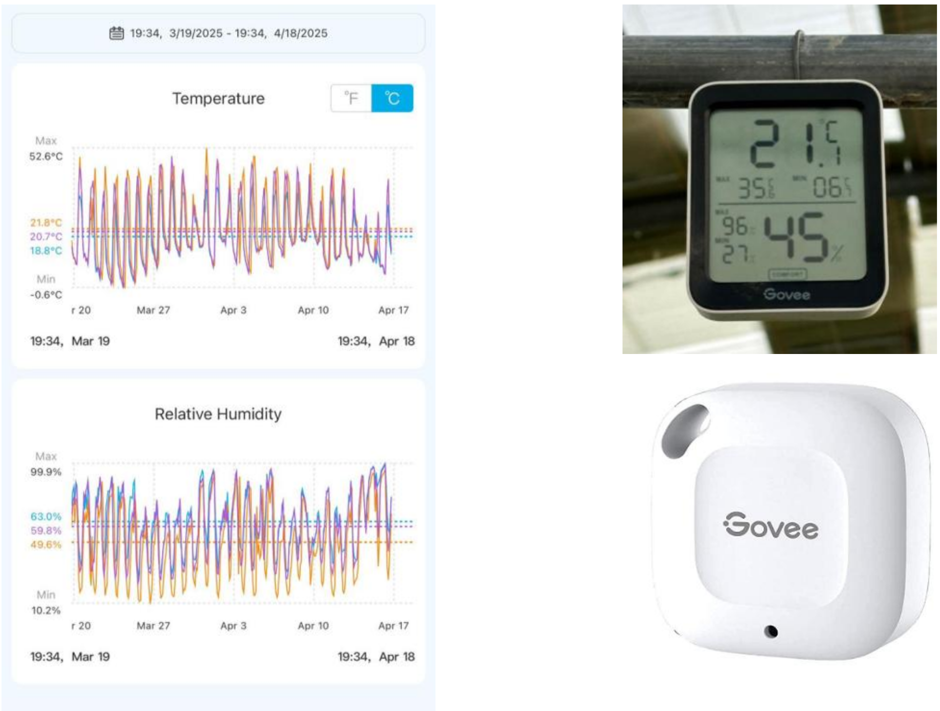


Figure (4): Govee smart thermo-hygrometer [Source]

- ***Consumed and produced energy***: The electrical power produced by the photovoltaic (PV) panels was measured with a solar multimeter device from Elejoy (figure 5), recording the instant power output in watts (W). These readings were then summed over time and converted into daily and seasonal energy values in kilowatt-hours (kWh). Energy consumed (W) for the irrigation pump system was also measured in (kWh). The PV energy was compared with the recorded irrigation energy demand to assess the energy balance and determine surplus energy produced by PV panels.

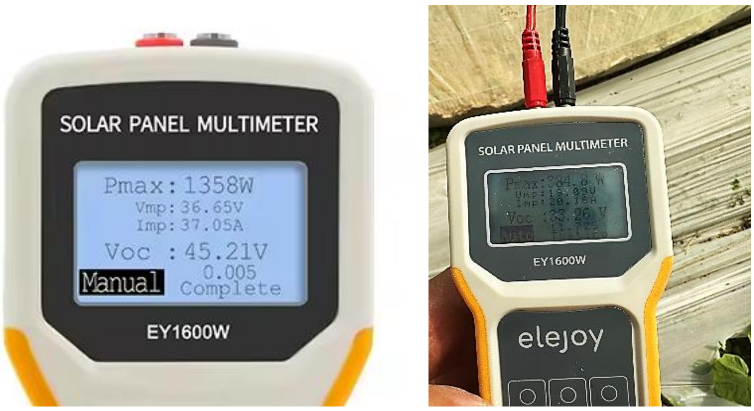


Figure (5): Solar panel multimeter [Source]

- **Early** ***crop***: the yield data for the early harvest of cucumber fruits were weighed (g.plant^{-1}) at full maturity to determine productivity per plant for both traditional and renewable systems. Nematode infection and subsequent treatment delayed the autumn planting date. Therefore, the yields from the first four harvests were counted before the decrease in temperature, under optimal conditions for cucumber fruit production. Based on this, the first four harvests were also counted in the spring to ensure a fair and unbiased analysis of the data.

- **Data Analysis:** The collected data were analysed using the General Linear Model (GLM) procedure in SAS OnDemand for Academics to assess the significance of differences among treatments at 5% probability level ($p < 0.05$). Mean comparisons were carried out using Duncan's Multiple Range test. The results were graphically presented to facilitate interpretation.

RESULTS AND DISCUSSION

Figures (6, 7, 8, 9) show the effects of the agricultural season, soil mulch type, and photovoltaic panel shading on temperature and humidity, energy production, and crop yield.

Temperature and Humidity of Shaded House

Both figures 6 and 7 demonstrate that the regularity of temperature variations due to the shading effect of the photovoltaic panels is reflected in the regularity of relative humidity variations in the greenhouse air resulting from cucumber plant transpiration. The increase in evaporation at 8 a.m. is due to the accumulated transpiration overnight, which decreases once the greenhouse doors are opened for ventilation. Furthermore, shading reduced temperature variations in the greenhouse for both seasons. Moreover, the coating played a clear role in the temperature variations inside the greenhouse. The black mulching contributed significantly to the retained temperature in the greenhouse (7.3 to 26.3°C in the Autumn season and 37.3°C in the Spring season, respectively), compared with the white mulching (7.8 to 18.9°C in the autumn season and 13.7 to 32.8°C in the spring season, respectively).

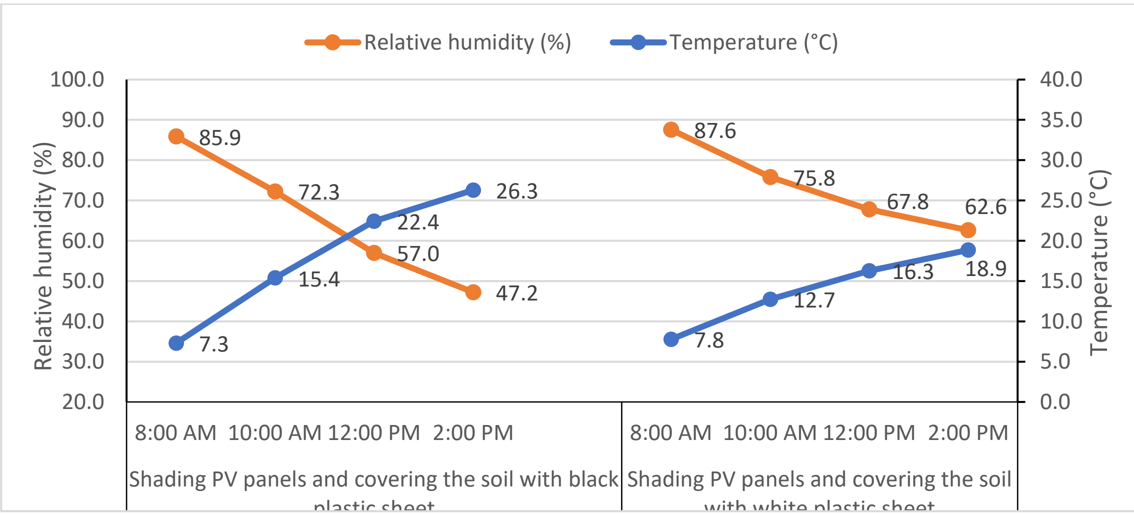


Figure (6): The impact of PV shading and soil mulch on temperature and relative humidity during the Autumn season in the tested greenhouses

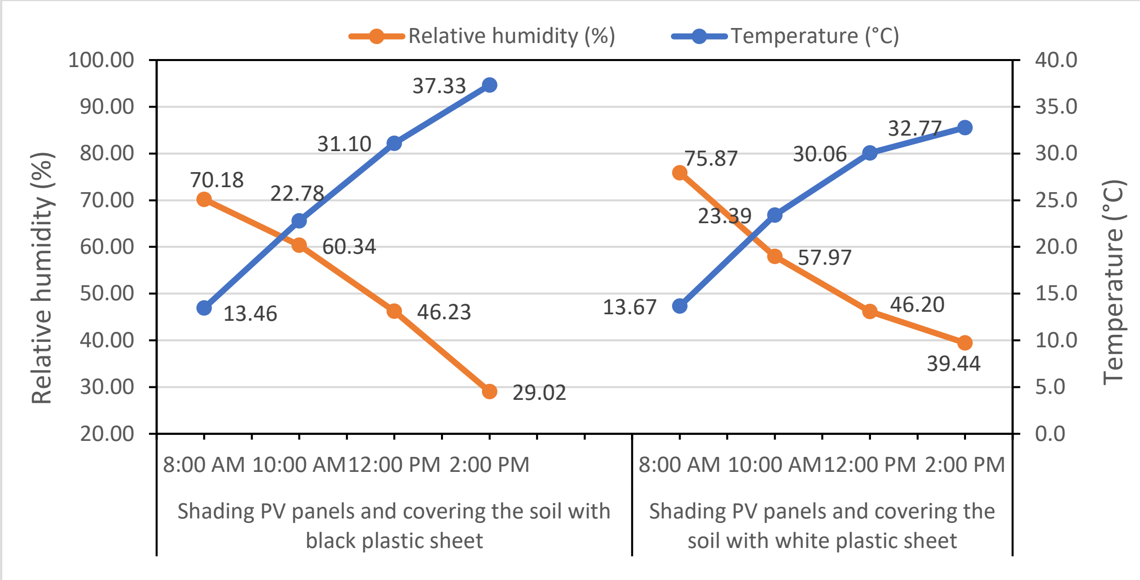


Figure (7): The impact of PV shading and soil mulch color on temperature and relative humidity during the Spring season in the tested greenhouses

Shading is not beneficial for crops, as each plant's ability to absorb light varies. However, it is essential to note that shading improves water use efficiency and reduces the impact of excess radiation during growth and fruit production (Omer *et al.*, 2025). Maintaining moderate temperatures inside the greenhouse reduces the relative humidity in the greenhouse air, which is caused by transpiration from the plants. The soil is completely covered, with no other source of water vapor except the plants themselves. Thus, the plant's lifespan will increase under suitable radiation and controlled temperature, reducing water stress on plants and extending the growing season. (Trommsdorff *et al.*, 2022)

Energy produced

Figure 8 shows that the energy produced by the PV panels used to shade the two greenhouses (172.74 kWh in the Autumn season and 176.98 kWh in the Spring season, respectively) is significantly greater than the energy required to pump irrigation water (60 kWh) in both seasons. Thus, the agrivoltaic energy excess amount was 112.74 kWh.Autumn season^{-1} and 116.98 kWh.Spring season^{-1}, respectively.

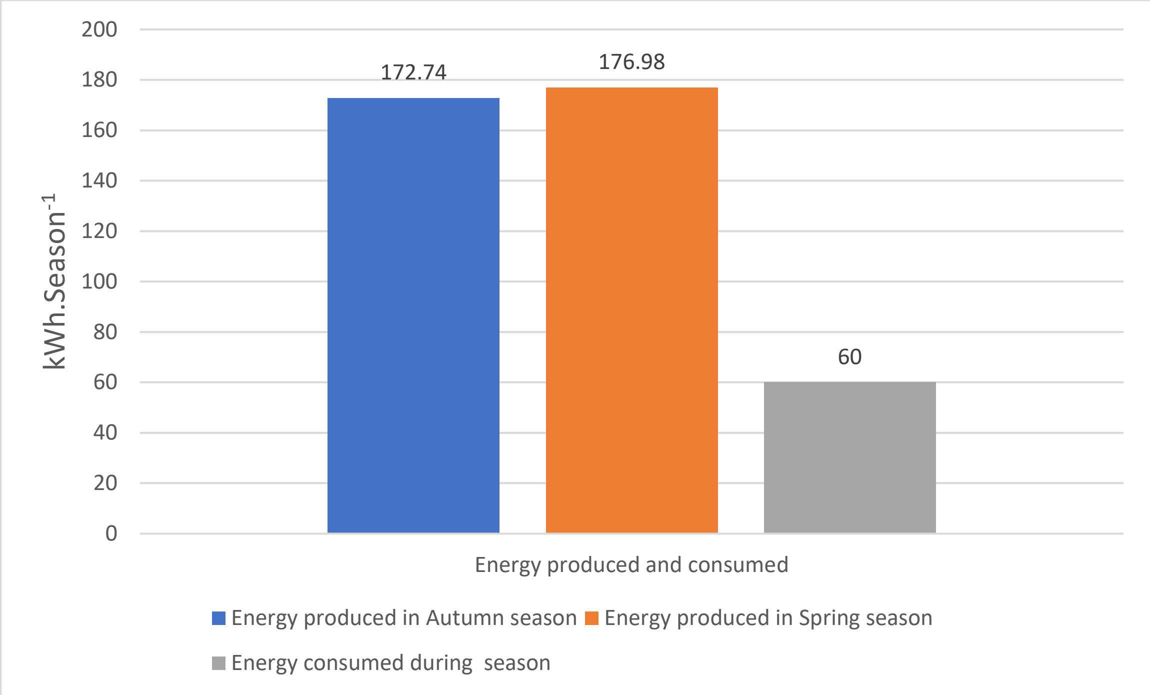
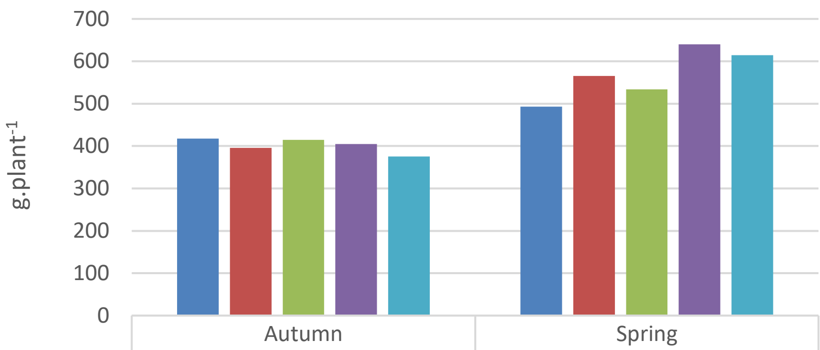


Figure (8): The energy produced by PV panels and the energy consumed by the irrigation process

Reduced crop production can be compensated for by the energy generated by the agricultural photovoltaic system (Kujawa *et al.*, 2025). Thus, supporting Even-lighting Agricultural Photovoltaic System (EAPV) controls the amount of light applied to the plants through the PV panels' shading. However, in reality, the intensity of solar radiation between 11:00 a.m. and 2:00 p.m. during spring, summer, and fall is extreme. It may even harm crop growth in many areas of the Northern Hemisphere. (Liu *et al.*, 2023).

Early crop

Figure 9 clarifies that the cucumber yield in the Spring season was better than in the Autumn season. This is mainly due to the low temperatures in the Autumn season, which decreased the cucumber yield. Cucumber production ranged from 395.8 to 417.6 g.plant^{-1} compared to 375.2 g.plant^{-1} in the traditional unshaded greenhouse for the autumn season. In the spring season, the cucumber yield ranged from 493.1 to 640.3 g.plant^{-1} compared to 614.3 g.plant^{-1} in the traditional unshaded greenhouse. Next comes the mulching colour, as black absorbs more heat, which partially raises the temperature of the greenhouse when combined with white. This is beneficial in autumn but stressful in spring. Hence, shading the photovoltaic panels came into play, reducing temperature variation, especially between 10 a.m. and 2 p.m.



	Autumn	Spring
White soil mulch & solid PV panels	417.35	493.13
White soil mulch & flexible PV panels	395.79	565.23
Black soil mulch & solid PV panels	414.76	533.49
Black soil mulch & flexible PV panels	404.77	640.33
traditional greenhouse	375.23	614.28

Figure (9): The cucumber yield amount at two seasons 2024-2025, under two PV panels and two soil mulching colors

There was no significant difference in the shading effect between rigid and flexible PV panels. However, both reduced the radiation reaching the plants in the shaded greenhouses without significantly decreasing the yield. The results were comparable to the cucumber yield in the unshaded conventional greenhouse. Trommsdorff *et al.*, (2022) noted that agricultural aspects contain four factors that contribute to the effectiveness of shaded plants in greenhouses: light availability, light management, microclimatic impact, and suitable crops. Additionally, shading generally reduces water stress on plants, thereby improving water use efficiency. However, yield is affected by the amount of shade, which involves the plants' ability to absorb light to the appropriate saturation level.

CONCLUSIONS

In this research, the following points can be concluded:

1. Both colours of greenhouse soil mulching were tested, which eliminated the process of water evaporation from the soil compared to a conventional greenhouse, thus reducing the relative humidity in the greenhouse atmosphere.
2. Shading with both types of photovoltaic panels helped reduce temperature variations, thus reducing water stress through transpiration.
3. The increase in production of the autumn season cucumber fruit ranged between +20.56, +29.54, +39.53, and +42.12 g.plant^{-1}, respectively. In contrast, crop production ranged from a shortage of -121.15 g.plant-1 to +26.05 g.plant-1 for the spring season. The shortage in cucumber production can be offset by the surplus electricity generated by photovoltaic panels, as in the last point.

4. The dual use of greenhouses achieved an energy increase of 112.74 kWh. Autumn season^{-1} and 116.98 kWh.Spring season^{-1}, respectively. This is exactly what efficient land use through dual production (energy and food) means, which compensates for the shortage in crop production.

ACKNOWLEDGMENTS

The authors would like to thank the University of Mosul for some of the laboratory equipment needed to complete this research and make it successful.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper. The research was conducted objectively, and no financial or personal relationships influenced the study's outcomes.

تأثير تظليل الألواح الكهروضوئية ولون تغطية التربة في استهلاك الطاقة وإنتاجية الخيار في البيوت البلاستيكية

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الخلاصة

أصبحت الزراعة في البيوت المحمية عاملاً فعالاً متزايد الأهمية في الزراعة الحديثة، اذ توفر الزراعة المحمية بيئة خاضعة للرقابة ومناسبة للمحاصيل على مدار العام. أجريت تجربة ميدانية لثلاث بيوت بلاستيكية غير مدفأة (اثنان للتجربة والثالث للمقارنة) لاختبار تأثير تظليل الألواح الكهروضوئية (صلبة ومرنة) المثبتة فوق سطح البيت البلاستيكي وتغطية التربة بالكامل بنايلون البولي إيثيلين (ابيض واسود) غير الشفاف في درجة حرارة الهواء الداخلي والرطوبة النسبية، كما دُرس تأثير التظليل في الإنتاج الأولى للخيار خلال فصلي الخريف والربيع 2024–2025 في قضاء تلكيف بمحافظة نينوى، شمال العراق. تم تحليل البيانات احصائياً وفق التصميم التجميعي لتبيان الفرق بين الموسمين. ولوحظ ان التغطية الكاملة تقلل من التبخر من تربة البيت بشكل كبير، وباقترانها مع التظليل ساعدت على تقليل الاختلافات في درجات الحرارة والرطوبة داخل البيت المحمي. تراوحت الاختلافات في درجات الحرارة في البيت المظلل باستخدام اللون الأسود لتغطية التربة في كلا الموسمين على التوالي، من 5.9 إلى 11 درجة مئوية. وكانت في البيت المظلل باستخدام التغطية البيضاء، من 6.2 إلى 13.9 درجة مئوية في كلا الموسمين على التوالي. حقق التظليل الناتج من الالواح الكهروضوئية لكلا النوعين، مع تغطية لكلا اللونين، زيادة في الحاصل المبكر للخيار في فصل الخريف مقارنةً بالبيت التقليدي، حيث تراوحت الزيادة بين +20.56 و+42.12 غ.نبات$^{-1}$. وعند مقارنة إنتاجية البيت المظلل بالألواح الكهروضوئية لفصل الربيع مع البيت التقليدي، تراوحت النتائج بين −121.15 و+26.05 غ.نبات$^{-1}$، وكانت كمية الحاصل المبكر (الجنيات الأربعة الاولى) (غرام.نبات$^{-1}$) أعلى من إنتاجية فصل الخريف. وقد عوّضت كمية الزيادة في

الطاقة هذا الانخفاض في إنتاجية محصول الخيار، حيث بلغت +112.74 كيلوواط.ساعة$^{-1}$ لفصل الخريف و+116.98 كيلوواط.ساعة$^{-1}$ لفصل الربيع على التوالي.

الكلمات المفتاحية: إنتاجية الخيار، انظمة الطاقة الشمسية، تظليل البيت المحمي، طاقة الألواح الكهروضوئية.

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