Adaptive Photochromism and thermochromism PV panels

"Theoretical design"

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Abstract:

This paper presents a theoretical study on the effects of visible sunlight on photovoltaic (PV) panels and the solar cells. It seemed that the red light has the most effect on the silicon solar cells. A theoretical study on the sunlight effects on the plants was done. It seemed that the more the blue light is, the greater and thicker the leaves will be and the shorter the stem will be. However, the red light is very important for flowering and blooming. This was confirmed by an experimental study on a sweet basil plant. The experimental results show that confirming the blue light increases the aroma intensification in the sweet basil leaves. A theoretical study on thermochromism and photochromism dyes leads to the adaptive photochromism and thermochromism PV panels designs that we present in this paper. .

Keywords*:Spectral Response, photochromism dye, Leuco Dye, thermochromism dye, Thermochromism Liquid Crystal(TLC), solar cell, PV greenhouse.*

1. Introduction

Many of PV stations have already been applied and coupled to the electric systems in most of the countries in the Levant Region. Most of those countries are agricultural, and they depend on agriculture to support their economy and achieve their food security. Therefore, it is very important to start planting the crops in PV greenhouses instead of nylon greenhouses. In this way, they could produce large amounts of electric power alongside keeping the crops and, even more, improving them.

Some of the PV greenhouses around the world use organic solar cells called Wavelength Selective PV systems (WSPVs). These greenhouses make energy from unused light while allowing most of the photosynthetic band of light to pass through because plants only use some wavelengths of light for photosynthesis. What’s more, these solar cells are effective insulators, because they reflect infrared light and this helps to keep greenhouses cooler in summer, while trapping more warmth in winter (LUMO- boldbusiness, 2020; Loik et al., 2017).

Some studies show that silicon solar cells have the biggest output when operate under red to infra-red light, because photons in the red light have enough energy to produce the photoelectric or photovoltaic effects (Deziel, 2018).

Red light is very important for plants, and it is responsible for flowering, seeding and fruit formation, whereas the blue light is important for leaves and stems. The more light the plants receive from the blue-violet and blue spectrum, the greater and thicker the leaves will be and shorter the stems will be (Max, 2019).

Experimental results on the sweet basil aromatic plant show that when we confirm the blue light, the leaves become greater, thicker and more numerous. The concentration of the fragrance increases in the leaves, and their colour will become bluish green. The flowering will not occur and the leaves will turn around the flowers, so they may wilt and die.

A thermochromism material like liquid crystal is able to switch their colour between two or more colours, when the temperature crosses up or down certain degree (Thermochromism–Wikipedia, 2020). Another material is photochromism like Leuco dye, which could switch its colour between two cases according to the changes in light intensity (Leuco dye – Wikipedia, 2020).

In this paper, the researcher presents new adaptive theoretical designs of thermochromism and photochromism PV panels. These panels could help improve the crops in PV greenhouses and improve the output of the PV panels.

2. The effect of solar energy wavelength on electron energy:

The energy of light photon is determined by Plank's law: $E = h.f$, where f is the frequency of the light vibration, and (h) is Plank's constant. We could use the wavelength (w) of the photon to write Plank's law as: $E = h.c/w$, where (c) is the speed of light. When the sunlight falls on a material, if the photons have enough energy, they could knock out some of the electrons. Some of the sunlight wavelength will produce the photoelectric or photovoltaic effects. In other words, only part of the solar spectrum is useful for generating electricity (Deziel, 2018).The main factor that affects solar cell efficiency is:

Minimum and maximum wavelengths: In general, the solar cell consists of PN-junction. This PN-junction has a specific band gap that differs from one material to another, and it is 1.11 EV for the silicon. Since one EV=1.6*10-19J, so the silicon band gap is 1.78*10-19J. According to Plank's law, the wavelength of the light that produces electric effects in silicon cell is: w=h.c/E=1.11nm, and it is very near infrared range (Deziel, 2018). The spectral response is the ratio of the current generated by the solar cell to the power incident on the solar cell (PVCDROM, 2020).

3. The effect of solar energy wavelength on plant:

3.1 Some of the visible spectrum of sunlight and infrared:

The visible sunlight has the wavelength range of 380-740nm (Ogherohwo et al., 2015). It consists of seven colours:

Red light: we could see the natural red colour at the sunrise or sunset. This is because the red and orange colours are not properly scattered by the atmosphere at sunrise or sunset, compared to the wavelength of other colours (Ogherohwo et al., 2015).

Green Light: All of the colours in the visible part of the spectrum are absorbed by the grass except for green, which explains why the grass is green.

Blue Light: The atmosphere scatter blue wavelength more efficiently, and so we see sky to be blue (Ogherohwo et al., 2015).

Violet Light: The violet and blue are more efficiently scattered by the atmosphere as other wavelengths, and where the human eye is more sensitive to the blue colour, and so we see sky blue and not violet (Ogherohwo et al., 2015).

Infrared Light: Infrared (IR) radiation belongs to electromagnetic radiation spectrum. It has a wavelength that is longer than the visible light, and it could be sorted out as redder-than-red light or "beyond red" light; that is why the name infrared (Ogherohwo et al., 2015).

3.2 The effects of visible sunlight spectrum on plants:

The leaves respond to the sunlight falling on it within 390-700nm wavelengths (Max, 2019). Plants store the collected sunlight energy as carbohydrates. A minimum amount of blue light is required, while a larger portion of red and far-red light is required, compared to the blue light. More blue light will lead to shorter stems and thicker leaves. Too much far-red light or an unequal balance with the red light will result in elongated plants. A low red to far-red ratio and consequently a limited amount of red light at the beginning of the night is important for the flowering of short-day plants (CANN, 2020). At the dark period, the plant regenerates and develops flowers (exciteled.de, 2020).

3.3 Plant's response to different light spectra:

Blue-Violet and blue light: When the plants receive more blue-violet and blue spectrum, the leaves will be greater and thicker and the stems will be shorter. Conversely, a decrease in the amount of blue light will cause a larger leaf surface area and longer stems. The blue light has an important role in the regulation of the stomata, water balance and CO_2-exchange, the natural development as well as control of phototropism (exciteled.de, 2020 ; CANN, 2020). If the plant does not get enough blue, it will start getting weaker, with yellow streaks in the leaves instead of green ones (Max, 2019).

Green light: The green light is slightly or not at all absorbed by the plants (exciteled.de, 2020).

Red and far red light: The effects of red light on plants is similar to the effects of the blue light (exciteled.de,2020). However, because the red and far-red light have a higher wavelength, they are less energetic than the blue (CANN,2020). The red light is important for flowering and blooming (Max, 2019).

4. Applications of smart windows:

The smart windows technology is new for buildings windows. That is, the windows thermal insulation properties were enhanced to reduce energy consumption. They may have a notable optical change from transparent to reflecting. In other applications, they could convert to photovoltaic panels.

4.1 Thermochromic smart window:

Vanadium dioxide (VO2) structures were developed for glass surfaces to enhance their thermal insulation properties in smart windows. VO2 thermochromic material exhibits a notable optical change from transparent to reflecting in the infrared upon a semiconductor to metal phase transition (Cao et al., 2018).

4.2 Switchable photovoltaic windows:

Switchable photovoltaic windows technology combines the benefits of smart windows with energy conversion by producing a photovoltaic device with a switchable absorber layer that dynamically responds to sunlight (Lance et al.,2017). Deep analyses were carried out on dark- and illuminated I–V curves, and dark C–V curves in (Dharmadasa et al., 2019).

4.3 Multi-colour semi-transparent organic solar cells with both efficient colour filtering and light harvesting:

The multi-coloured semi-transparent organic solar cells (TOSCs) design containing metallic nanostructures with a high colour purity and efficiency based on theoretical considerations works as an efficient colour filter that selectively transmits light with the desired wavelengths and generates electricity with other wavelengths (Wen et al., 2014).

5. New technologies of solar cells and solar collectors:

5.1 Wavelength-selective degradation of perovskite-based solar cells:

Vlad et al. (2020) tested the perovskite solar cells with red, NIR and blue lights. The cell performance under illumination with the red light decreases insignificantly. The photovoltaic parameters of the cells have increased with the exposure time under NIR, because NIR irradiance has improved the perovskite stoichiometry.

5.2 Thermochromic coatings for overheating protection of solar collectors:

Antonio et al. (2013) used thermochromic coating to cover the solar collectors in order to limit the stagnation temperature of solar collectors to a value below the boiling point of the heat transfer liquid without degrading the optical performance of the selective coating during normal operation.

5.3 Wavelength-Selective Solar Photovoltaic Systems:

Greenhouse roofs were considered a piece of prime real estate and were very useful for solar energy in many countries (LUMO- boldbusiness, 2020; Loik et al., 2017). LUMO panels are used to cover the greenhouses roofs. These panels combine efficient greenhouse growing with solar power production. LUMO panels use a luminescent dye to convert the green light not efficiently used by plants into beneficial red light. The LUMO uses photovoltaic cells in a patented interdigitated array developed by the Solaria Corporation. Dye concentration has been selected so that the light removed by the cells is offset by the increase in usable red light from the dye, Fig 1, (LUMO PANEL – soliculture, 2020). These LUMO solar panels are Wavelength Selective Photovoltaic (WSPV) systems.

a **b**

Fig 1: Wave length selective PVs, b- The lower luminescent layer, (LUMO PANEL – soli-culture, 2020)

6. Thermochromism and photochromism:

Thermochromism is the property of substances to change colour due to a change in temperature, while photochromism changes colour due to change in light intensity (Thermochromism– Wikipedia, 2020). Thermochromic materials change colour at specific temperatures (Thermochromic pigments, 2020). The two most common approaches of thermochromism are Thermochromism Liquid Crystals(TLCs) and Leuco dyes. Liquid crystals are used in precision applications, as their responses can be engineered to accurate temperatures, but their colour range is limited by their principle of operation, while Leuco dyes allow a wider range of colours to be used, but their response temperatures are more difficult to set with accuracy (Thermochromism– Wikipedia, 2020). Leuco-dyes can be mixed in various ways to produce all kinds of colour-changing effects at a wide range of everyday temperatures. Leuco-dyes are much cruder indicators of temperature than Liquid Crystal because they are just indicating cold versus hot with one simple colour change. That's because all that they can do is switching back and forth between their two different forms (leuco and non-leuco). Both TLCs and Leuco-dyes can be printed on the surface of other materials in the form of microscopic capsules (Chris, 2019).

Liquid Crystals are like solids in some respects and liquids in others. When the light falls on, some of the light will reflect back again in a type of reflection known as iridescence; the same phenomenon that makes colours from the scales on a butterfly's wing and the surface of a soap bubble (Chris, 2019). Some liquid crystals are capable of displaying different colours at different temperatures depending on the selective reflection of certain wavelengths by the crystallic structure of the material (Thermochromism– Wikipedia, 2020). Typically, the high temperature reflects blue-violet, while the low-temperature reflects red-orange, Fig 2, (Thermochromism– Wikipedia, 2020).

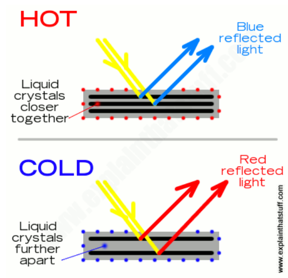


Fig 2: Liquid Crystal (Thermochromism– Wikipedia, 2020).

Arno et al. (2013) developed the first non-toxic and non-carcinogenic thermochromic polymer material, in this technology, the temperature changed in a way detectable by the human eye without any kind of auxiliary.

7.Practical experiences:

7.1The effects of sunlight on sweet basil, experimental results:

In order to corroborate theoretical ideas, the researcher compared between two sweet-basil plants, which are odorant grass like plants. One was put in blue-green glass's light; the other one was put in natural sunlight. After 6 months, the researcher noticed that the leaves, which were in blue light, were very big in size and number with very bluey green colour as shown in Figure 3a. The flowering never happened because the leaves had been torrential around the blossoms and flipped upside down to cover them as shown in Figure 3b, and the aroma intensification was much intensified. However, the plants in the natural sunlight had a normal number and size of green leaves. It naturally blossomed, flowered and seeded, and the aroma intensification was not intensified as shown in Table 1. The researcher noticed that the experimental results have corroborated the theoretical ideas above.

The researcher later put back the studied plant in full sunlight for a month. The big size leaves have withered and fallen off, and were replaced by new small ones as shown in Fig 3c.

Table 1: A Summary of different Radiation Interception by plant adaptation to blue wavelength confirming

object	**Blue glass (blue light)**	**natural sunlight**
total leaf area	huge, thicker	medium
number of leaves	high- hoarded	medium-normal
leaf area distribution	convergent	divergent
amplitude of the foliar area curve	torrential	normal
orientation of the head leaves	upside-down	normal
leaves around blossoms	torrential around blossoms	under blossoms
sweet basil head	thick	elongating
stems	shorter	longer
the aroma intensification	intensified	not intensified
flowering and blooming	never blooming	blooming
seeds	not seeded	naturally seeded

a **b** **c**

Figure 3: a- The leaves after 6 months, b- The leaves cover the blossoms, c- The plant in full sunlight.

The researcher put the "Aptenia cordifolia" behind a clear blue "vibra" plate for four hours a day for 10 days as shown in Figure 4a. From the second day of the experiment, the researcher noticed that its response was amazing; its color began to get greener, and the size of its stems began to increase, and the number of the growing peaks increased as shown in

Figure 4b.

The researcher could conclude that for green corroborate or trefoils or grasslike plants, it is useful to use blue-green glass to cover.

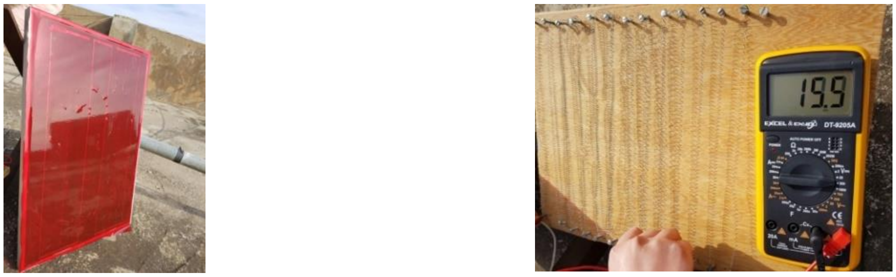
a **b**

Figure 4: "Aptenia cordifolia" at the second day , b- "Aptenia cordifolia" after 10days.

7.2 The red covering of the PV silicon-cells panel:

First, the researcher has measured the output voltage of a loaded PV panel in a hazy cloudy day, and consequently the values ranged between 17V to 17.5V. Then, the researcher has applied a red covering of the PV panel with a red transparent adhesive as shown in Figure 5a. Then, the output voltage was measured every 5 minutes for half an hour; the values ranged between 19.1 to 19.9V as shown in Figure 5b. Then, the coverage was removed manually, and the output voltage was measured. It was noticed that it decreased immediately to 18.1V.

The researcher could conclude that the red coverage of the PV panel has increased the output voltage of the silicon-cells PV panel.



a b

Figure 5: a- PV panel with red cover, b- The output voltage.

8. Photochromism and thermochromism PV panels:

According to the above study, we could conclude that:

1- PV cells are usually dark because they are coated with a non-reflective material.

2- The band gap energy for silicon is 1.11 ev, which is the material used most often for solar cells, so the bandwidth wavelength for silicon solar cells is in the very near infrared range.

3- According to the experimental results, red covering of the silicon-cells PV panels increases the output voltage.

4- The more light plants receive from the blue-violet and blue spectrum, the shorter the stems will be and the greater and thicker the leaves will be. If a plant does not get enough blue light, it will start getting weaker, with yellow streaks in the leaves instead of green.

5- Red and far-red must be available for the plant, and the effects of red light on photosynthesis are similar to the effects of the blue light. However, because the red and far-red light have a higher wavelength, they are less energetic than the blue. The red light is essential for the flowering and blooming of the plants. Deficiency in this light wavelength will invariably result in delayed flowering or very weak blooming stage in plants.

6- The experimental results on sweet-basil and "Aptenia cordifolia" have corroborated the theoretical ideas above.

7- Thermochromic smart window, Switchable photovoltaic windows, TOSCs are the technologies in which the glass changes between two cases of transparent or electric mode.

8- WSPVs and perovskites are PV technologies that are suitable for electric generating and crops growth. LUMO uses a luminescent dye layer to convert the green light not efficiently used by plants into beneficial red light. Dye concentration has been selected so that the light removed by the cells is offset by the increase in usable red light from the dye.

9- Thermochromism is the property of substances to change colour due to a change in temperature, while photochromism changes colour due to the change in light intensity.

According to the considerations above, the researcher suggested to paint the glass-layer of the PV panels with photochromism or thermochromism and de-space the solar cells and degrease their number in an adaptive technology, which was named Photochromism and Thermochromism PV panels. The researcher presented the adaptive photochromism and thermochromism PV panel technology in following three applications:

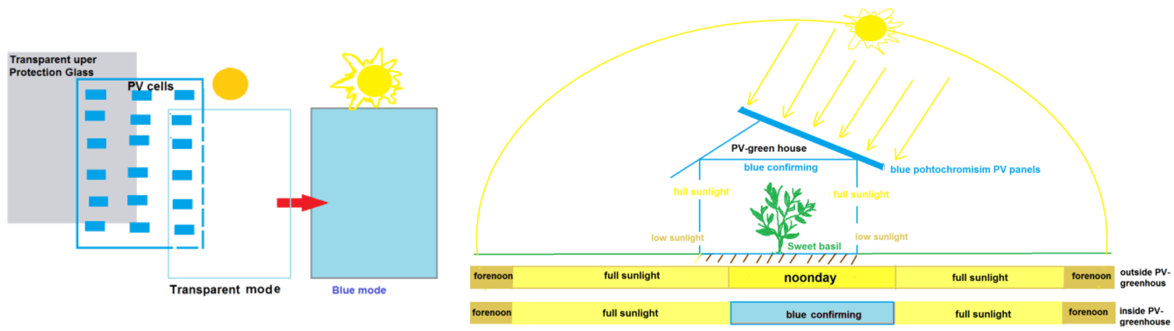
8.1 Blue photochromism PV panels for confirming the blue light for the odorant grasslike plants in PV greenhouse:

According to the experimental results on sweet basil and "Aptenia cordifolia", the researcher noticed that confirming the blue light had enhanced the plant form (bigger in number and size of the leaves, shorter stems and thicker leaves) and the aroma intensification. In order to confirm the blue light for the odorant grasslike plants in PV greenhouse, keep the upper protection glass layer and replace the lower protection glass layer of the panel with a blue photochromism layer and decrease the number of the solar to let the light get through. This blue photochromism layer operates in two optical modes as shown in Figure 6a:

1- Transparent mode at the day extremes, when the sunlight is attenuate.

2- Blue light mode during the day when the sunlight is violent, absorbing all the sunlight except the blue light (this well protect the plant from high temperature).

At the beginning of the day, when the sunlight is attenuate, the photochromism layer operates at the transparent mode. The full sunlight gets to the plants through the spaces between cells and the solar cells work at their normal operation conditions. At noon, when the sunlight is violent, the photochromism layer switches to the blue light mode in order to confirm the blue light. In the afternoon, the photochromism layer switches back to the transparent mode as shown in Figure 6b.

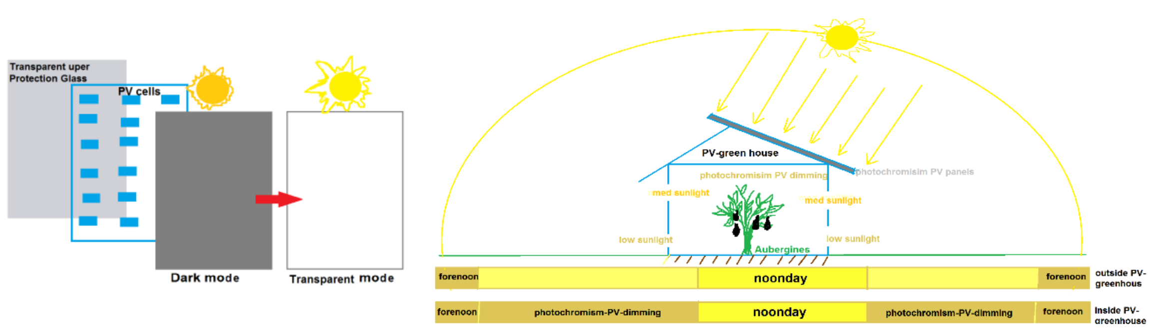


a B

Figure 6: Blue photochromism layer modes, b- Blue photochromism layer operating.

8.2 Dark photochromism PV panels for reducing lighting duration in PV-greenhouse:

Some groups like aubergines need longer dark duration to speed up the fruits maturating. Replacing the lower layer by a photochromism dark layer makes the dark period of the day longer as shown in Figure 7a. This photochromism dark layer operates in two modes: the dark mode at the day extremes, when the sunlight is attenuate and the transparent mode during the day when the sunlight is violent as shown in Figure 7b.



a B

Figure 7: a- Dark photochromism modes, b- dark photochromism operating.

8.3 Red thermochromism PV panels for improving silicon PV panel efficiency:

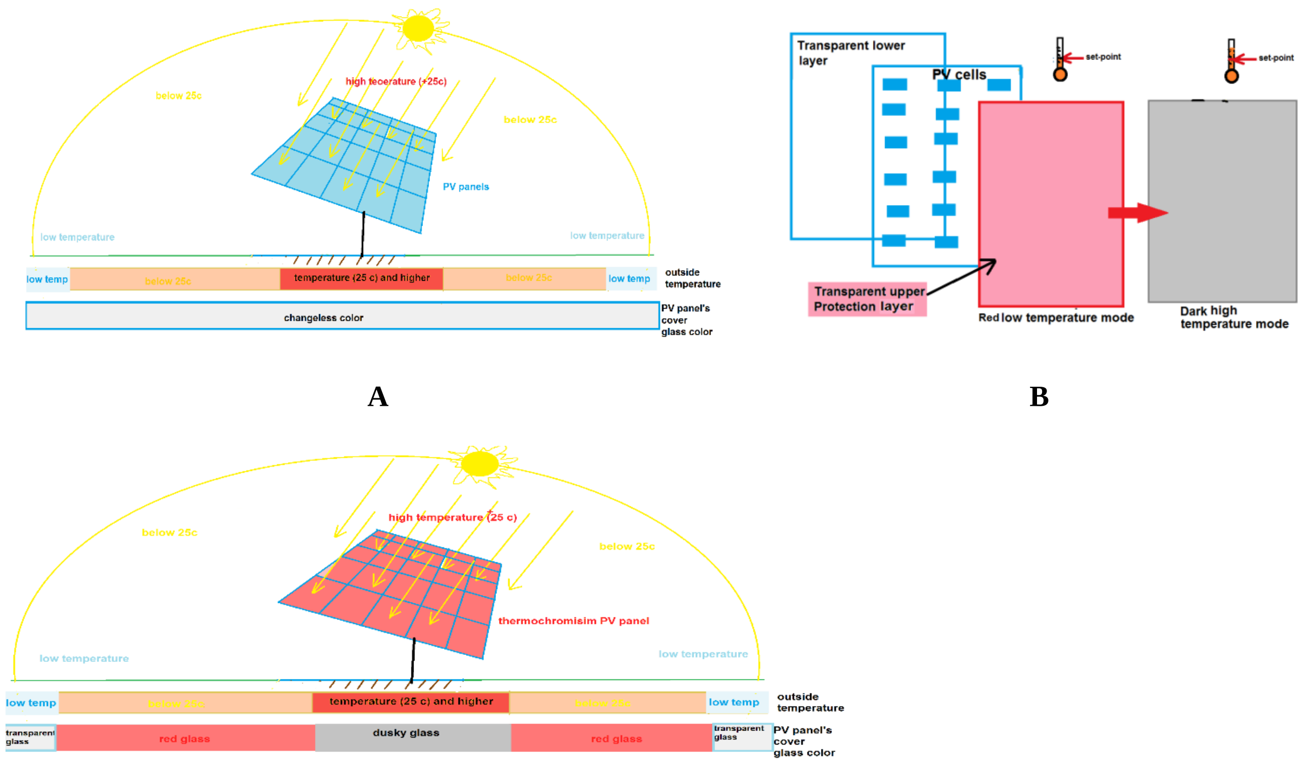
Traditional PV panels have dark upper protection glass layers. These layers remain dark all during the day, as shown in Figure 8a. Replacing the upper protection glass layer with a red thermochromism layer improves the silicon PV panels’ efficiency. This layer will operate in two modes as shown in Figure 8b:

1- Red mode at the day extremes, when the sunlight is attenuate and the temperature is below certain degree (set point).

2- Dark mode, at noon, when the sunlight is violent, absorbing all the sunlight (this well protect the PV cells from high temperature).

At the beginning of the day, when the temperature is below the set point, the thermochromism layer operates at the red mode. This will confirm the red light to the silicon solar cells, and increase the value of their output. At noon duration, when the temperature overpasses the set point, the thermochromism layer switches to the dark mode, and the solar cells work at their normal operation conditions. In the afternoon, the thermochromism layer switches back to the red mode as shown in Figure 8c.

Note: The researcher could set the set point temperature during the manufacturing operations at a convenient point, at which the silicon PV cells operate well.



c

Figure 8, a- Traditional silicon PV panel, b- Red thermochromism modes, c- Thermochromism operating.

9. Conclusion

Confirming the blue light for the odorant grasslike "Sweet Basil" and "Aptenia cordifolia", enhances the plant form (bigger in number and size of the leaves, shorter stems and thicker leaves) and intensifies the aroma. Applying the red coverage on silicon-cells PV panel increases the output voltage. Apply the blue photochromism PV panels for confirming the blue light for the odorant grasslike plants in PV greenhouse. Apply dark photochromism PV panels in order to reduce the lighting duration in PV-greenhouse. Using red thermochromism PV panels may improve the silicon

PV panel efficiency. Those three application ideas are still theoretical, which may be efficient applications in practical studies

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ألواح كهروضوئية تكيّفيّة متغيرة اللون ضوئياً أو حرارياً

دراسة نظرية

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الملخص:

تمّ في هذا إجراء دراسة نظرية لتأثير ضوء الشمس المرئي في الألواح الكهروضوئية والخلايا الشمسية، وتبيّن أنّ للضوء الأحمر التأثير الأكبر في عمل الخلايا الشمسية السيليكونية. كما تمّ إجراء دراسة نظرية لتأثير ضوء الشمس في النباتات، وتبيّن أنّه كلّما تعرّض النبات للضوء الأزرق، تصبح الأوراق أثخن وأكبر حجماً، بينما تصبح السوق أقصر. وبيّنت الدراسات أنّ الضوء الأحمر ذو أهمية كبيرة في عمليات إزهار النباتات وازدهارها.

وتمّ تأكيد النتائج النظرية من خلال تجربة عملية قمنا بها على نبات الحبق العطري، وتبيّن أنّ تعزيز الضوء الأزرق قد أ سهم ـ إلى جانب ما تمّ ذكره في الدراسات النظرية- بزيادة تركيز العطر في أوراق الحبق.

ومن خلال الدراسات المرجعية للصباغ المتغيّر اللون حرارياً وضوئياً، تمّ التوصل إلى التصميم النظري للألواح الكهروضوئية التكيّفية المتغيّرة اللون ضوئياً أو حرارياً التي تمّ اقتراحها في هذا البحث.

الكلمات المفتاحية: ***الاستجابة الطيفية، الصباغ المتغيّر اللون ضوئياً، الصباغ المتغيّر اللون حرارياً، الصباغ الأبيض، الكريستال السائل المتغيّر اللون حرارياً، الخلايا الشمسية، البيوت الزراعية الكهروضوئية.***