The impact of coloured filters on the performance of polycrystalline photovoltaic (PV) panel in an uncontrolled environment

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ABSTRACT

Photovoltaic modules behave extraordinarily by transforming part of the visible spectrum into electrical energy, and their efficiencies are affected by the nature of radiation (light) reaching them. When light strikes a photovoltaic cell, this light may go through the cell without been absorbed if it is too energetic or if the light possesses low energy it will be absorbed by the cell and cause the electrons to twist and vibrate in their bonds without dislodging them, hence causing the cell to heat up which ultimately leads to a decrease in its overall efficiency. This study is aimed to investigate how photovoltaics respond to different wavelengths of light. For the study to achieve its aim, colour filters were used to ensure that only a particular wavelength of light reaches the photovoltaic module at a time. In the process of collecting data from the solar panel, the solar panel was placed horizontally flat on a platform one meter above sea level facing the sun. Data was first obtained from the solar panel without the filters and after that with the filters placed one at a time and data collected accordingly. The amount of solar power and solar flux anytime a different colour filter was placed on the solar panel were measured. Among the coloured filter used yellow produced the highest efficiency, while blue produced the least efficiency. However, the solar panel was still more efficient when exposed to the natural spectrum.

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1. INTRODUCTION

Solar energy has been seen as a viable solution towards energy, environmental, and global challenges. The burning of fossil fuels consistently has led to humans suffering from an energy crisis accompanied by the pollution of our environment. Solar energy has received intense attention because renewable energy is on tremendous focus [1]. Photovoltaic systems are now seen as the most promising and reliable renewable source of energy in Africa and the middle east due to its abundant solar irradiation [2].

The earth receives an enormous amount of energy from the sun in the form of light. It is impossible for the human eye to detect all the radiations emitted from the sun because some are not in the visible spectrum. Each of the visible and invisible radiations of the solar spectrum has its distinct energy. The relative values are dependent upon the optical properties of the transparent object and the solar spectrum [3]. The visible part of the electromagnetic spectrum comprises of wavelengths from red to violet, and violet is at the high-energy end (having half again more energy as the red light) while red is positioned at the low-energy end. Radiation in the ultraviolet region (which is invisible but causes the skin to become tanned) has more energy than that in the visible region, while radiation in the infrared region (which is unseen but been felt as heat) has less energy than that in the visible region [4].

In the process of light striking a silicon crystal, this light may go through it; it may be reflected or be absorbed. Usually, when the light of relatively low energy is absorbed by a solid, heat is created without tempering with the electrical properties of the material. This low energy light causes the silicon atoms to twist and vibrate in its defined position, but unable to break loose [4]. Due to this vibration, electrons in bonds acquire more energy and attain a higher energy level, which they are unstable. Consequently, they give off heat as the energy acquired while returning to their original lower energy level. This heat emitted by the electrons comes to increase the overall temperature of the silicon cell, which plays a significant role in decreasing its efficiency [5]. The technology of solar photovoltaic (PV) is among the essential sources of renewable energy. Since the early discovery of the PV effect by Alexandre E. Becquerel in 1839, solar cells have received steady improvements towards its performance [6]. Recently solar energy has attracted attention and is playing a vital role in providing clean and sustainable energy [7]. However, researches that are related to the nature of semiconductors used in solar cells have limited systems that incorporate photovoltaic technologies to the efficiency of 15-20%. Thus, to improve PV system efficiency, some modifications and improvements, such as applying maximum power point tracking controllers and sun trackers, have been incorporated into PV system designs [8]. Usually, it is expected that photovoltaic cells are designed to give out the most ideal output. Some factors influence this typical output, and they can be classified as unchangeable variables and volatile variables. The unchangeable variables by default need to be adapted to while the changeable variables enable flexibility in design so that installation requirements can be taken care of. These variables (unchangeable and changeable) affect the design and configuration of a photovoltaic panel, its operation, and installation, and also play a significant role in the generation of solar power [8].

The government of Nigeria has recently improved its effort towards the utilization of photovoltaic technology due to a few factors, such as an increase in the cost of oil, global warming (unnatural changes in weather conditions), and the need for constant power supply. Presently in Nigeria, the use of photovoltaic technology is applied to very few areas such as telecommunications mast, highway, street, garden lightning, rural electrification, and parks. The efficiency of solar photovoltaic systems may be among the reasons why it is not yet widely applied in Nigeria; hence there is a need for further research to be carried out on photovoltaic systems under the Nigerian climate. As for now, solar photovoltaic systems are applied to specific areas in Nigeria merely to provide additional power or to provide backup power in moments of fluctuating power supply or power outage. Photovoltaic (PV) solar systems were first developed to meet the electrical needs of isolated areas, such as islands, mountain regions, and the rural regions of developing countries. Since the early 2000s, the development of solar photovoltaic systems has grown exponentially [9]. Unfortunately, solar characteristics rely on ecological conditions like irradiance intensity and temperature [10]. Njok et al. [11] found that high solar power and solar flux positively enhance the performance of photovoltaics. This result was made known after a thorough investigation of the influence of solar power and solar flux on the efficiency of polycrystalline solar photovoltaics installed closed to a river. Kazem and Chaichan [12] studied how coloured filter influence the output parameters of a PV panel and found that the PV gave its highest efficiency under the natural spectrum compared to the other spectrum of light. Ali et al. [13] analyzed how the performance of a photovoltaic cell is influenced by the visible colour spectrum and reported that the red colour of light profoundly affects modern photovoltaic technology. The study also reveals that the energy of a PV system lies between the yellow and green colour of light. Tobnaghi & Naderi [14] carefully examined how the performances of solar cells are affected by solar radiation and revealed that the performances of solar cells are highly dominated by solar radiation. El-shaer et al. [15] discovered that the current parameter in a crystalline silicon solar cell is the parameter that is mostly influenced. Chegaar et al. [16] reported that the short circuit current in a solar cell is what is significantly affected after researching on how solar cell parameters are affected by illumination intensity.

Joshi et al. [17] investigated the effect light colour have on the performance of a PV/T system and found that the red colour of light dramatically influences present-day photovoltaic technology. It was further revealed that the energy available on the surface of the PV/T system lies between the wavelengths of orange and red light. Chaichan & Kazem [18] carried out an experimental analysis of how solar intensity influence photovoltaic modules in humid and hot weather conditions and reported that the effect of wind on modules temperature was insignificant for the period in which the experiment was carried out. Schubert and Spinner [19] researched solar simulator spectrum and measurement uncertainties and found that a solar simulator made of 19 led lights can be compared to an industry-standard filtered xenon solar simulator.

Ogherohwo et al. [20] investigated how the wavelength of light influence the performance of solar photovoltaic module, and reported that the red colour of light led to the production of more electricity from solar photovoltaic panel and concluded that solar panel efficiency could be improved if a way could be devised to expose a solar panel to only red light. Bicer et al. [21] reported that the solar spectrum of low wavelength enables higher efficiency in PV cells and hence hydrogen production after studying the effects of various solar spectra on photovoltaic cell efficiency and photonic hydrogen production. Njok et al. [22] investigated how sunrise and sunset times cause monthly variations in photovoltaic efficiencies and reported that photovoltaics would be more efficient in months with low average relative humidity coupled with low panel temperature. Lee et al. [23] found that the generation of electricity with a conversion efficiency of up to 3% can be achieved with ultrathin a-Si/organic hybrid cells. It was also revealed that higher efficiency should be possible with optimization. These results were brought to light after research was conducted on coloured ultrathin hybrid photovoltaics with high quantum efficiency. Pravettoni et al. [24] proposed an alternative method for measurements to be undertaken on large-area thin-film photovoltaic modules in terms of spectral response.

A solar photovoltaic panel exposed to the sun receives radiation containing different wavelengths of light. Some wavelengths are very long (example infrared); hence they possess relatively low energy, which only causes electrons to vibrate in their bonds without dislodging them, thereby leading to an increase in the overall temperature of the solar panel which decreases its efficiency. Also, some wavelengths are too short (example ultraviolet) and possess relatively high energy that goes through the solar panel without being absorbed but only causes the photovoltaic to heat up. The aim and novelty of this study lie with the meticulous investigation of the impact of coloured filters on the performance of solar photovoltaic systems installed in an atmosphere close to the river for residential household use, which in Nigeria's prospect is not yet investigated. For the study to achieve its aim, colour filters were used to ensure that only a particular wavelength of light reaches the photovoltaic module at a time.

2. MATERIAL AND METHODS

2.1. Materials

A solar photovoltaic module with a power capacity of 130 watts made from polycrystalline silicon was used in the process. This module possesses a dimension of 1480*670*35 mm and is capable of delivering 18.10V and 7.18A at maximum voltage and current, respectively. Different coloured (five colours) filters were employed to separate the light from the sun into different wavelengths. A charge controller was used to enable steady and smooth charging of the lead-acid battery (12V-75AH). A digital multimeter (M890C+) possessing an accuracy of ±0.8% and ±2.0% for DC voltage and DC current, respectively, synchronized with a thermocouple (K-type) for measuring temperature in Celsius was employed to monitor the current and voltage values accurately. A mastech digital solar flux meter (MS6616) with an accuracy of ±3% was used to monitor the variations in solar flux carefully. A digital solar power meter (SM206) possessing an accuracy of ±5% was also utilized, which is capable of measuring solar power in British thermal unit (Btu) and in Watt per square metre (W/m^2).

2.2. Methods

A platform raised to a height of one metre above sea level was built, and the solar panel was horizontally placed flat on it facing the sun, as can be seen from Figure 1. Connecting cables linked the output terminal of the solar panel and the charge controller. From the output of the charge controller, a cable was connected to the battery to ensure smooth charging. While the load was powered through an inverter connected to the battery.

Measurements were taken at an interval of 30 minutes from 6.00 am to 6.00 pm for 90 days. During measurements, each colour filter was placed one at a time after measurements had been taken from the panel exposed to the natural spectrum. Using a digital multimeter, the voltage and current were measured. By the use of a digital lux (light) meter and a digital solar power meter the amount of solar flux and solar power reaching the panel when a colour filter was placed were measured respectively. Figures 2-4 show the solar panel covered with the different colored filters.

From the readings obtained, the power from the solar panel was determined using in (1), the maximum power that the solar panel can give out can be calculated using in (2), while the normalized power output efficiency was calculated using in (3) as shown by [25]. It also indicates that the short circuit current and the open-circuit voltage have been influenced by parameters like solar power and temperature, as indicated in (4) and (5). It has been shown by [26] that the efficiency of a photovoltaic module can be determined using in (6).

2.3. Equations

Measured power:

$$Pmea = V_{mea} \times I_{mea} \quad (1)$$

Maximum power:

$$Pmax = V_{max} \text{ x } I_{max} \quad (2)$$

Normalized power output efficiency:

$$\eta_p = \frac{P_{mea}}{P_{max}} \times 100 \quad (3)$$

Short circuit current:

$$Isc = bH \quad (4)$$

Open circuit voltage:

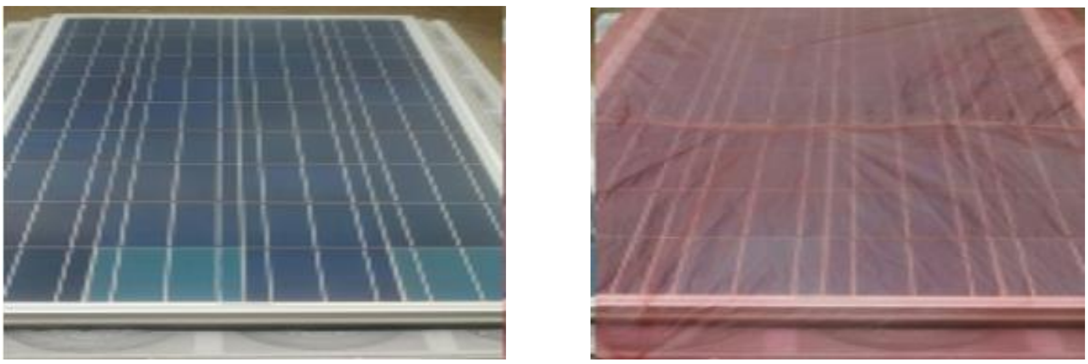
$$V_{oc} = \frac{KT}{Q} ln \frac{Isc}{Io} \quad (5)$$

Module efficiency:

$$\eta_{mod} = \frac{Power\ of\ solar\ panel \times 100\%}{Area\ of\ solar\ panel \times 1000W/m^2} \quad (6)$$

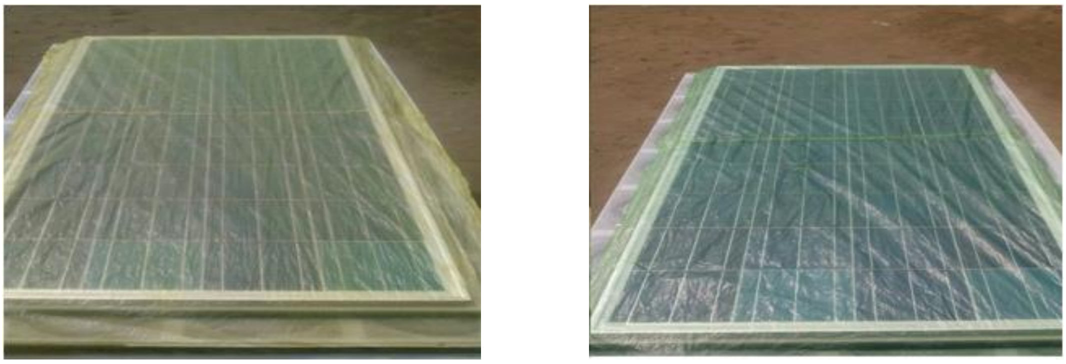
where P_{mea}, $V_{mea,}$ and I_{mea} are the measured power, voltage, and current, respectively. P_{max}, $V_{max,}$ and I_{max} are the maximum power, voltage, and current, respectively, that the module can give out. Q is the electronic charge, I_o is the saturation current, T is the absolute temperature of the photovoltaic module, b is a constant depending on the properties of the semiconductor junction, K is the Boltzmann constant and H is the incident solar power (light intensity) on the photovoltaic module.

Figure 1. Photovoltaic module and the coloured filters used placed on a platform one metre high



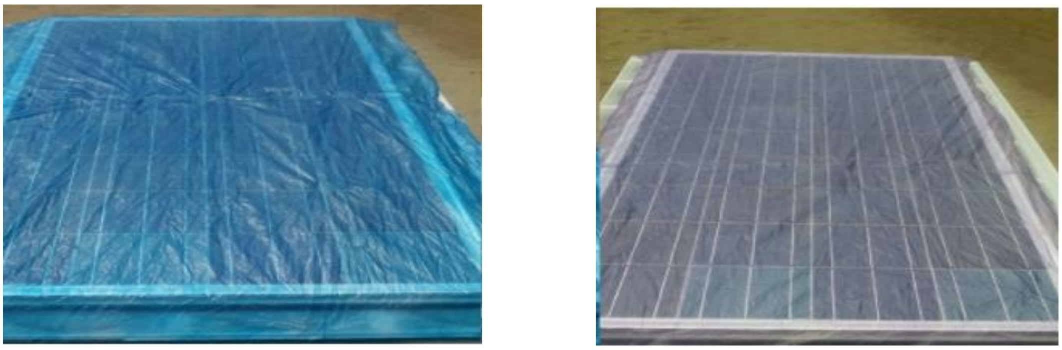
(a) (b)

Figure 2. Photovoltaic module without filter and with red coloured filter respectively,
(a) a photovoltaic module without filter, (b) photovoltaic module with a red filter



(a) (b)

Figure 3. Photovoltaic module with the yellow and green coloured filter respectively,
(a) photovoltaic module with yellow filter, (b) photovoltaic module with green filter



(a) (b)

Figure 4. Photovoltaic module with the blue and violet coloured filter respectively,
(a) photovoltaic module with blue filter, (b) photovoltaic module with violet filter

2.4. Study area

Calabar, the capital of Cross River State, is located in the southern part of Nigeria, situated on Latitude $4^0$57'06'' N and longitude $8^0$19'19'' E at an elevation of 32m above sea level. But the location selected for this study is on Latitude $4^0$57'38.6161" N and Longitude $8^0$18'58.482" E, it is about 400metre away from the Calabar River [1] as shown in Figure 5.

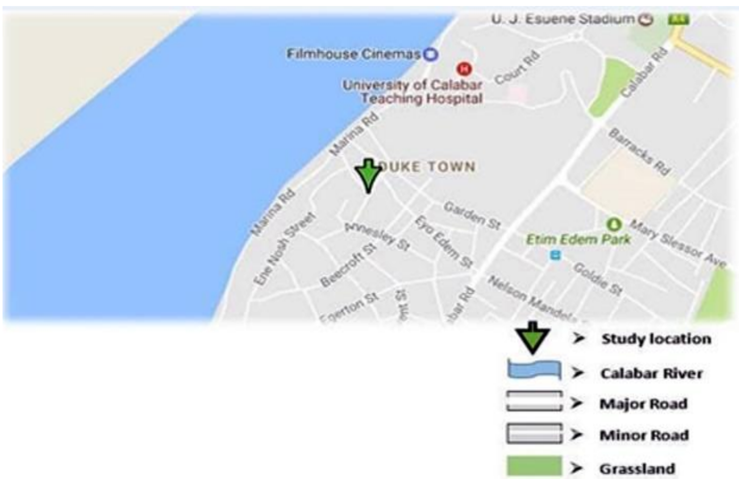


Figure 5. Map showing the study location [1]

3. RESULTS AND DISCUSSIONS

Figure 6 highlights how the photovoltaic module responds in terms of voltage production as the solar power reaching the module increases when covered with coloured filters. It shows that the same trend is observed with the coloured filters as without them. It also reveals that above 200W/m^2 of solar power, the voltage remains relatively stable for each filter colour. Figures 7 and 8 show the current production and the efficiency of the photovoltaic module under different coloured filters with increasing solar power, respectively. The photovoltaic module produced more current and attained a higher efficiency without the filters, while the lowest current and efficiency were observed when covered with the blue filter. For each coloured filter and without the filters, the current and efficiency increased linearly as solar power increased. The trends observed in Figures 7 and 8 agree with work by Ettah et al. [26].

Figure 9 is similar to Figure 6, and it shows the voltage produced by the photovoltaic module with increasing solar flux under different colour filters. For each filter and without the filters, an increase in voltage is observed from 0 to 20klux of solar flux reaching the panel. Above 20klux, the voltage remains relatively stable. Figures 10 and 11 show the current and efficiency of the photovoltaic module under different coloured filter with increasing solar flux respectively. The photovoltaic module produced more current and reached a higher efficiency without the filters, while the lowest current and efficiency was observed when covered with the blue filter. For each coloured filter and without the filters, the current and efficiency increased linearly as solar flux reaching the panel increased.

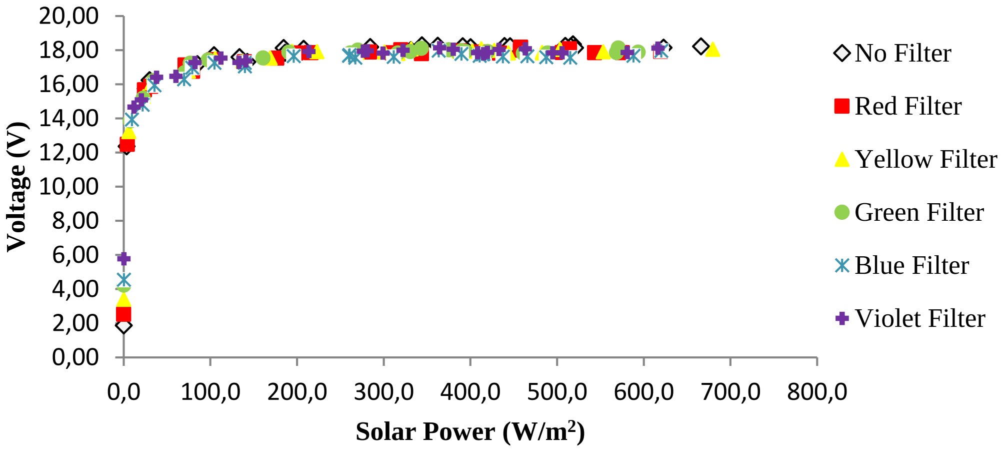


Figure 6. Effect of solar power on voltage; voltage performance for the different filters

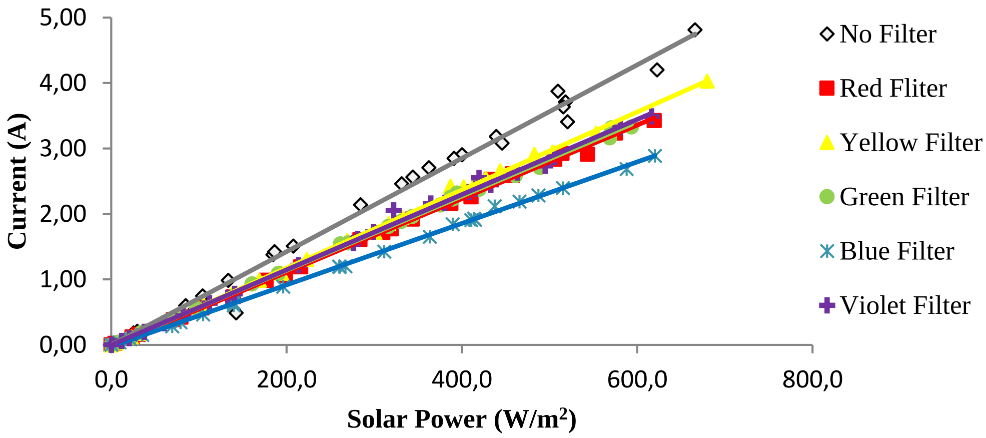


Figure 7. Effect of solar power on current; current performance for the different filters

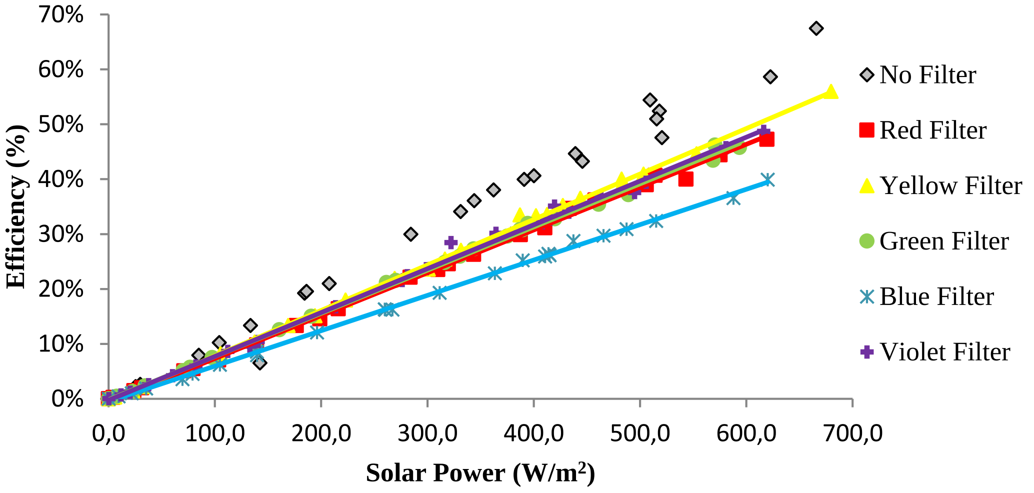


Figure 8. Effect of solar power on efficiency; module efficiency for the different filters

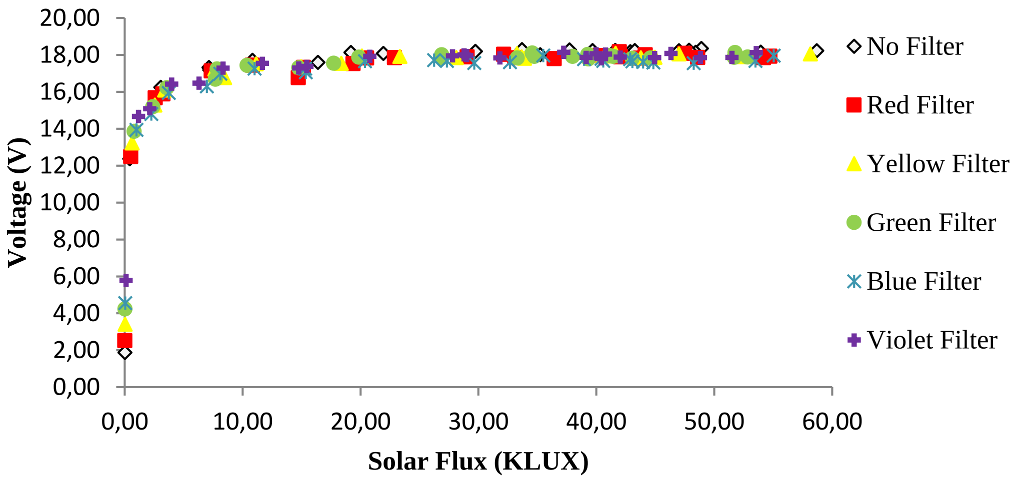


Figure 9. Effect of solar flux on voltage; voltage performance for the different filters

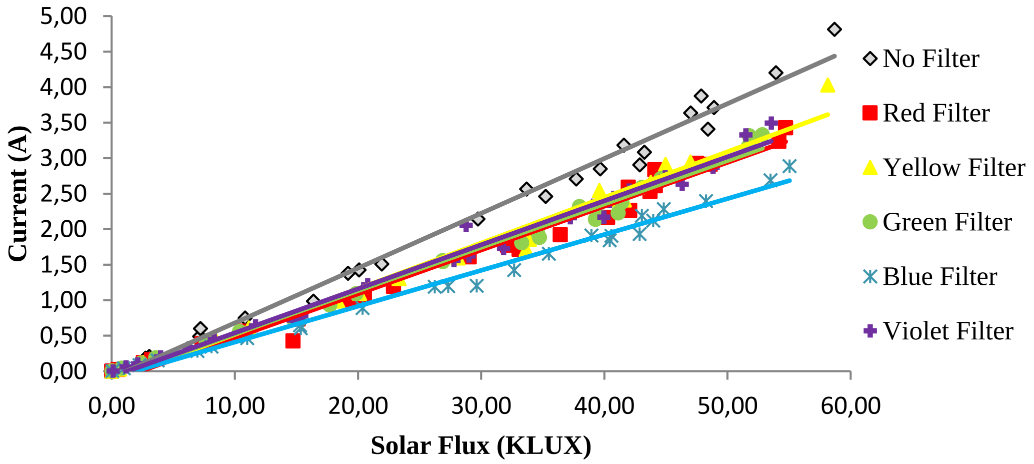


Figure 10. Current performance for the different filters (uncontrolled environment)

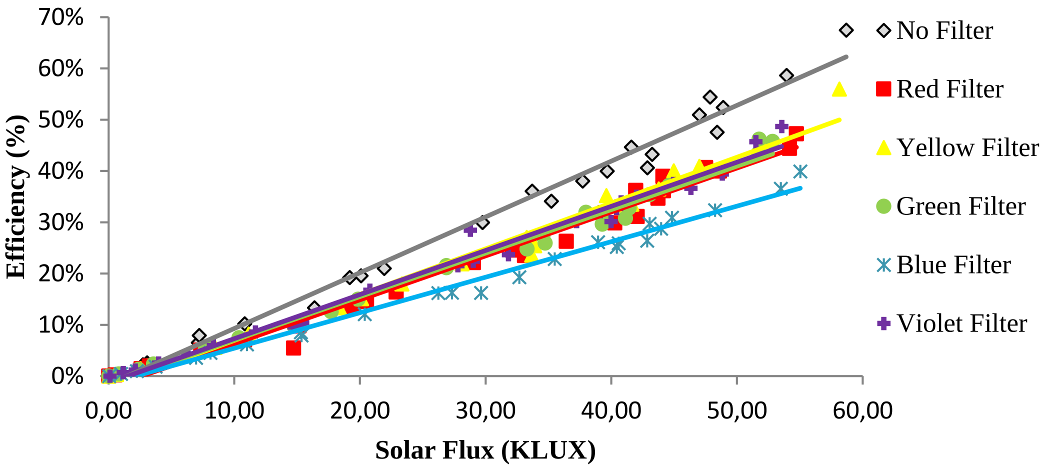


Figure 11. Module efficiency for the different filters (uncontrolled environment)

Figure 12 displays the maximum voltage produced by the photovoltaic module under the different coloured filters. The highest voltage (18.35V) was produced when the photovoltaic module was exposed to the natural spectrum. With the coloured filters, the photovoltaic module produced the second-highest voltage (18.17V) under the red filter, while the least voltage (17.97V) was produced under the blue filter. This result agrees with studies by Ogherohwo et al. [20].

Figure 13 depicts the maximum current produced by the photovoltaic module under the different coloured filters. It shows that the yellow filter produced the highest current (4.03A) followed by a violet filter with 3.49A. The least current (2.89A) was produced with the blue filter. However, the photovoltaic panel was most effective in current production (4.81A) when exposed to the natural spectrum. This result disagrees with studies by Kazem and Chaichan [12].

Figure 14 shows the maximum efficiency reached by the photovoltaic module with and without the coloured filters. The highest efficiency (67%) from the photovoltaic module was achieved under the natural spectrum; with the coloured filters, yellow gave the highest efficiency (56%), followed by violet (49%) and blue giving the lowest (40%). Red and green filters gave 47% and 46% respectively. Figure 15 displays the average efficiency during the day, which the photovoltaic module can give out with and without the filters. Without the filters, an average of 30% efficiency was attained. With the filters, yellow gave the highest average efficiency (23%); blue gave the least average efficiency (18%), while red, green, and violet all gave an average efficiency of 22%.

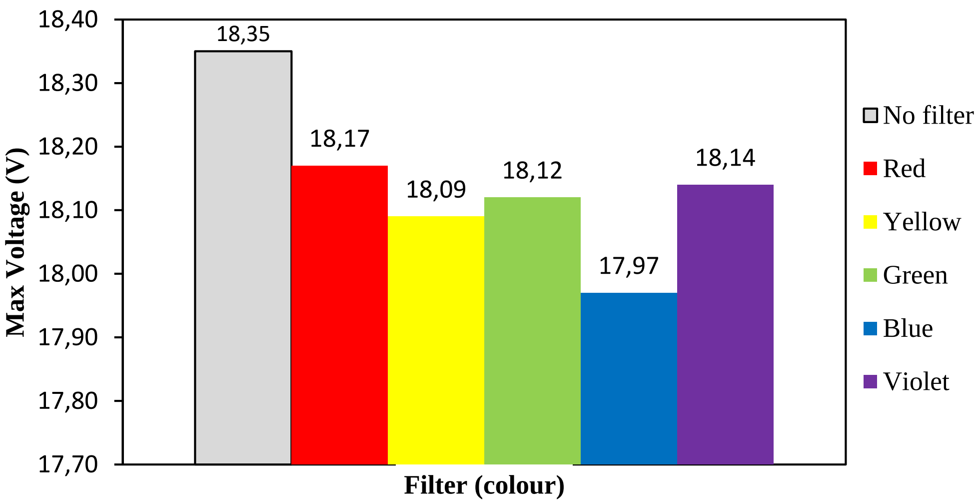


Figure 12. Maximum voltage produced by each filter (uncontrolled environment)

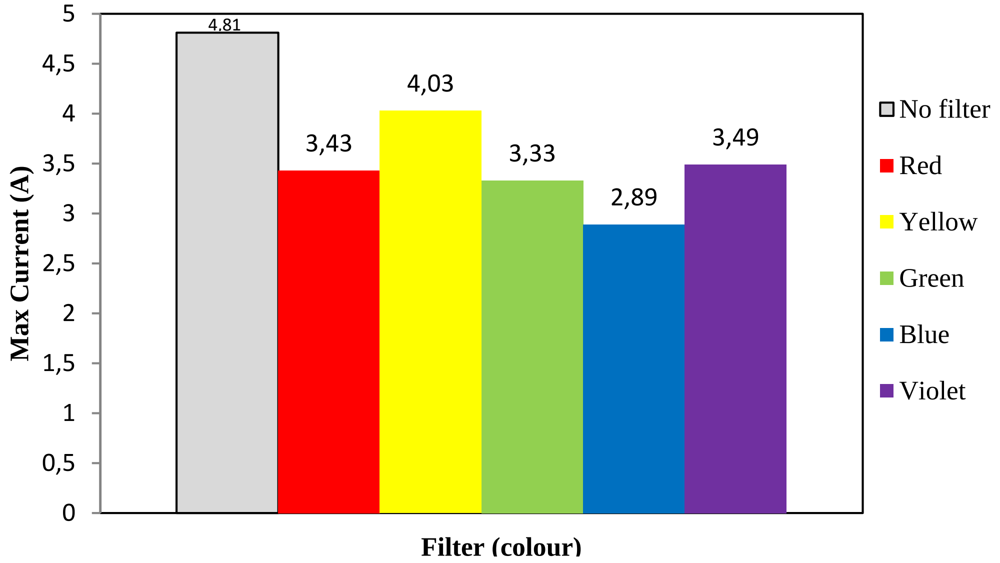


Figure 13. Maximum current produced by each filter (uncontrolled environment)

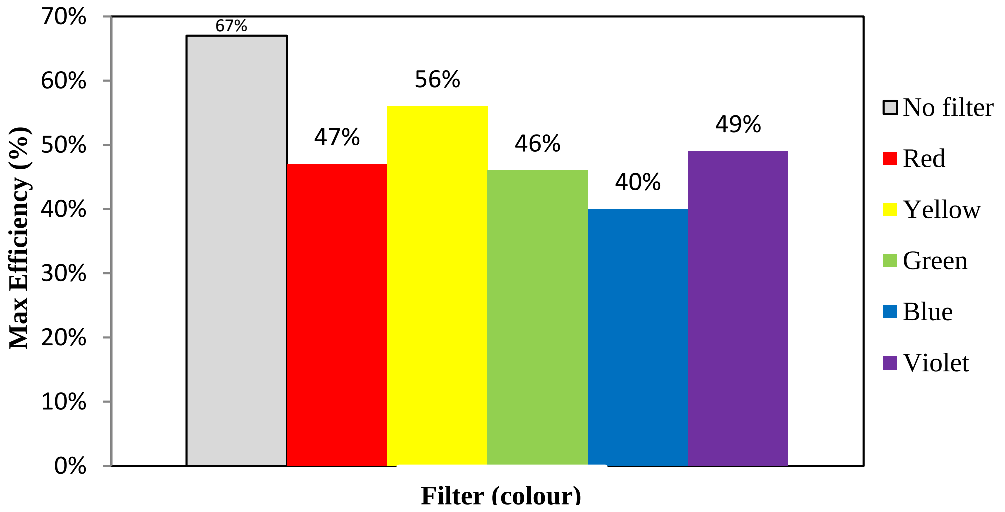


Figure 14. Maximum module efficiency produced under each filter (uncontrolled environment)

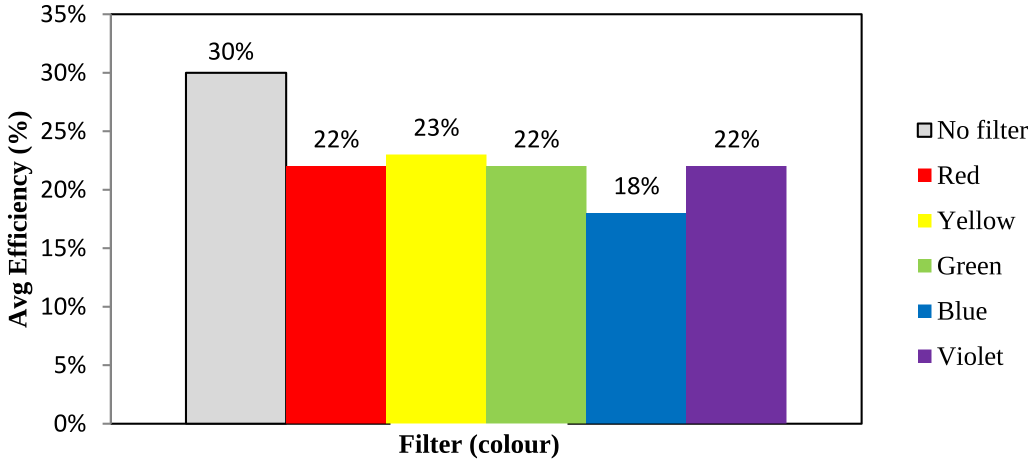


Figure 15. Average module efficiency during the day under each filter (uncontrolled environment)

4. CONCLUSIONS

Solar radiation is among the primary parameters that greatly influence solar photovoltaic (PV) outcomes. However, a group of wavelengths is what constitutes the solar radiation, and each wavelength has its influence on the solar cell. In the environment of the study location, photovoltaic modules are most efficient when exposed to the natural spectrum since the filter reflects and absorbs part of the light reaching the module. According to the theory of photoelectric effect, one would have expected the efficiency of the photovoltaic module to increase as the frequency of the light reaching the module increased. But the results of the study proved otherwise and show that polycrystalline solar photovoltaic panel responds more to yellow light (577–597nm). If a means could be devised for solar photovoltaic panels to be exposed to only yellow light without diminishing the intensity of light reaching it, then yellow light can outperform the natural spectrum of light. Moreover, the application of colour filters to solar photovoltaic panels will be beneficial in months and location that receives irradiance above 1000W/m^2, so that the transmitted radiation would be or close to 1000W/m^2.

DATA AVAILABILITY

Further experimental data if needed can be inquired via Email to the corresponding author.

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