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Hands-on Solar Energy: Exploring How Light Influence Solar Cell Performance in Junior High School Experiments

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Abstract

This study explores the impact of light wavelength on solar cell performance through a hands-on laboratory experiment designed for junior high school students. The experiment utilized a spectrometer app to measure the dominant wavelengths of various visible light colors and assessed the corresponding voltage and current generated by a solar cell. Results indicated a clear inverse relationship between wavelength and solar cell output, with shorter wavelengths producing higher voltage and current values. For example, light with a wavelength of 400 nm resulted in the highest voltage (1.75 V) and current (13.9 µA), whereas light at 650 nm generated the lowest output (1.43 V and 8.7 µA). This experiment provides an accessible, cost-effective way for students to grasp the principles of solar energy and wavelength effects, enhancing their understanding of energy conversion in renewable technologies.

Keywords: Laboratory activity, Solar cell, Experiment

INTRODUCTION

Science education curricula in Indonesia have been continuously improved due to the implementation of the freedom to learn curriculum (Prima et al., 2023). However, in accordance to the most recent survey, students need to be pushed to enhance their 21st century skills. According to Braaten & Sheth (2017) learning science managed by teachers fails to meet expectations due to an absence of practical skills. Fitri (2021) expressed an identical point of view, claiming that errors during experimentation and limitations in practical tools cause the teaching and learning process to run poorly, resulting in a lack of comprehension in students' minds. In most cases in Indonesia, science is presented in the classroom using only supplementary books, and students are not as involved in actual activities (Prima et al., 2023). Students must be engaged with the learning process if the goal is to achieve learning objectives and acquire a deep understanding of the lesson (Dwiyanti et al., 2021; Hamdani et al., 2022).

Science cannot be understood by memorizing facts or by passively listening to the teacher describe concepts. Students, on the other hand, must learn through experimentation, observation, and involvement, which will ultimately foster creativity and awareness. This process is crucial for maintaining and enhancing the study of natural phenomena, and it's also important for shaping scientific attitudes (Suryawati & Osman, 2018). According to Prima, Utari, Chandra, Hasanah, and Rusdiana (2018), changing perceptions of the values and purposes of science learning have increasingly emphasized the importance of laboratory work.

Physics is considered a challenging subject for students to learn. Physics topics are abstract and difficult for students to learn, leading to a lack of motivation and interest (Wangchuk et al., 2023). Students also struggle with determining the equations of physics formulas used to solve problems (Qotrunnada, 2022). The lack of engagement in learning physics is also considered a significant factor in students' difficulties with the subject (Ramadhani & Tanjung, 2020).

Given these conditions, this study aims to develop laboratory work that can assist school teachers in teaching the topic of wavelengths for eight grade students. The table 1 shows the core competences and basic competences in the curriculum. Wave science is perceived by students as difficult, abstract, and monotonous, often seen as a discipline suitable only for extraordinarily talented and gifted students (Erinosho, 2013). The concept of wavelength will be directly implemented into real-world scenario, a mini solar cell will be used as a main tool in the laboratory work. The importance of connecting science content and skills to real-world scenarios is crucial for enhancing students' understanding and engagement (Thomas et al., 2013).

Previous study on the development and implementation of laboratory activities in learning physics concepts has been conducted. A research by Knezek & Christensen (2020) insists junior high school students to analyze home inventory appliance that consume standby power. Meanwhile, Nicolaidis (2020) developed a portable organic solar cell kit for undergraduate and high school students. A study from Prima (2023) developed a low-cost experiment regarding the measurement of light wavelength using light diffraction phenomenon. Another research is from Angjelina (2023), a microcontroller-based hydrostatic pressure experiment tool has been developed. Rosyidah, Prima, & Riandi (2023) also developed laboratory activities using tracker software to calculate the speed of propagating waves on the water surface. However, there is still no research on the development of laboratory activities to investigate the effect of wavelength on the current and voltage output in a solar cell. Through this experiment, students can become more engaged in learning the concept of waves as it relates to real-world phenomena. Furthermore, the experiment can be conducted without the need for expensive or advanced tools.

Table 1. Core competence and basic competencies in grade 8 Junior high school

	CORE COMPETENCE 3 (COGNITIVE)		**CORE COMPETENCE 4 (PSYCHOMOTOR)**
3.	Understanding knowledge (factual, conceptual, and procedural) based on curiosity about science, technology, art, culture-related phenomena, and eyesight event.	4.	Trying, processing, and serving in the concrete realm (using, parsing, composing, modifying, and creating) and abstract realm (writing, reading, counting, drawing, and composing) according to what was learned in schools and other sources same in point of view/theory.
	BASIC COMPETENCIES		**BASIC COMPETENCIES**
3.11	Analyzing the concepts of vibration, waves, and sound in everyday life, including the human hearing system and the sonar system in animals	4.11	Presenting experimental results on vibrations, waves, and sound Analyzing the properties of light, the formation of shadows on flat and curved planes, and their application to explain the process of human vision, insect eyes, and the working principle of optical instruments.
3.12	Analyzing the properties of light, the formation of shadows on the plane flat and curved and its application to explain human vision process insects, and the working principle of optical instruments.	4.12	Presenting experimental results about shadow formation on mirrors and lenses.

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METHOD

Preparing The Materials

This research needs several tools and materials which are Android phone, multimeter, solar cell, wire, and solar power meter. These materials are shown in figure 1.

Figure 1. Tools and Materials

The light source for this experiment is an Android phone. Two Android phones are required, and each phone needs one application to be installed—Screen Lamp and Spectrometer. Both applications are available for free on the Google Play Store.

Variables

The experiment contains 3 kinds of variables which are independent, dependent, and controlled. Those variables are detailed in Table 2.

Table 2. Experiment Parameter

Parameter	Details
Independent	Wavelength variation from phone's screen (nm)
Dependent	Current (μA) and voltage (V)
Control	Light intensity of the phone's screen (0.2 W/m^2), distance between phone's screen to the solar cell (15 cm)

Procedures

The development of the experiment was started from October-December 2023. After through several steps, the experiment was completely developed. The flowchart of the development is shown in figure 2.

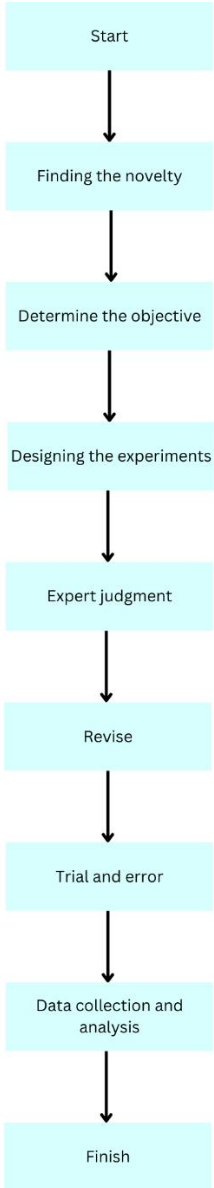


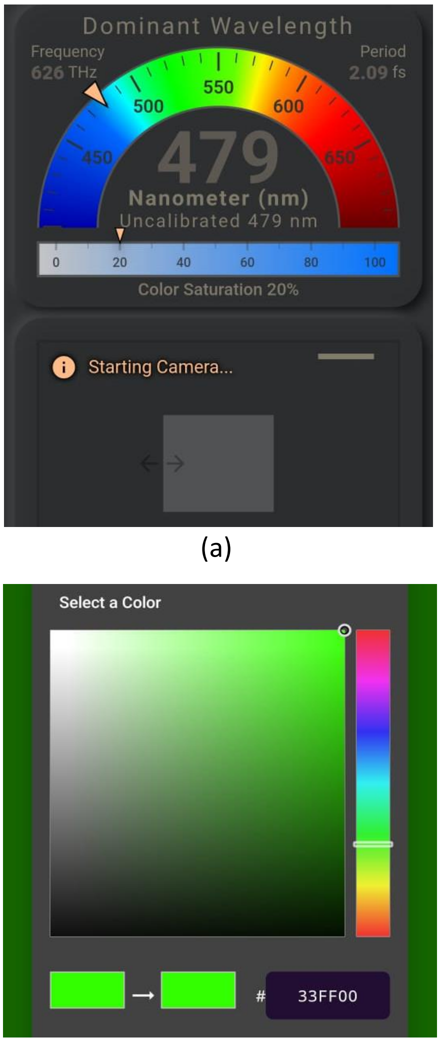
Figure 2. Flowchart of development

Preparing Hex Color and Wavelength

Using the Spectrometer and Screen Lamp applications, we can measure the wavelength emitted by the phone's screen. The wavelength we want to take in this experiment ranging from 400 nm, 450 nm, 500 nm, 550 nm, 600 nm, and 650 nm. The application display is shown in figure 3.

First, open the Screen Lamp application, and click the custom color button to set the hex code for the screen color. The hex color code is a six-digit code that signifies a specific color and is widely used in web design and digital media. Each pair of digits in the code represents the intensity of the color's red, green, and blue components. For instance, the hex code

#FF0000 represents the color red at its maximum intensity, with no green or blue. Hex codes are frequently used to ensure consistent color representation across different digital platforms.



(a)

(b)

Figure 3. The display of (a) Spectrometer and (b) Screen Lamp application

Second, on the other phone, open the Spectrometer application. Spectrometer allow the user to measure the dominant wavelength of the light, just by directing the camera to the light source. In this research, the source light is from Screen Lamp application, so just direct the camera from the Spectrometer application to the other phone. Set the hex code in the screen lamp application to meet the wavelength of 400nm, 450nm, 500nm, 550nm, 600nm, and 650nm.

Preparing Solar Power Meter

Solar power meter was used to measure the light intensity of the phone screen. The light intensity needs to be the same, otherwise the current and voltage output from solar cell is not fully affected by only wavelength, but also light intensity. The distance of phone's screen to the solar power meter needs to be the same also.

Preparing Solar Cell

The solar cell was connected to the multimeter, ensuring the correctness of the wire connection. After obtaining the specific hex code and wavelength, current and voltage measurements were conducted. The solar cell was placed inside the dark chamber, while the multimeter remained outside. The solar cell setting is shows in figure 4.

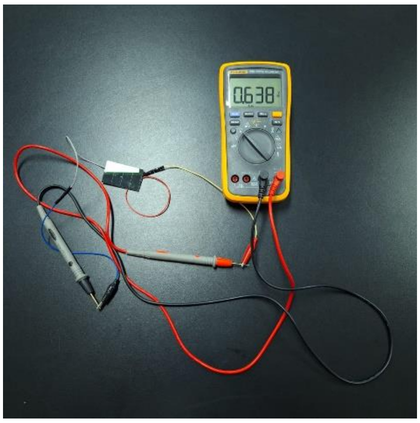


Figure 4. The display of (a) Spectrometer and (b) Screen Lamp application

Preparing The Cardboard Box

The measurements were conducted in a dark chamber to ensure the exclusion of any other light sources besides the phone's screen. The dark chamber was constructed using a cardboard box.

On the top side of the dark chamber, there is a hole designed to accommodate the Android phone. The Android phone is positioned facing the inside of the dark chamber, ensuring that the solar cell only receives light from the phone's screen. Additionally, a small hole at the bottom ensures the connection of the wire from the multimeter. The laboratory setting is illustrated in Figure 5.

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(a)

(b)

Figure 5. (a) The dark chamber and (b) laboratory setting for current and voltage measurement

Principles of PV Effect

The electricity generation in photovoltaic (PV) is referred as PV effect. Alexandre-Edmund Becquerel, a French physicist, discovered voltage transmission in 1839 after experimenting using an electrolytic cell made up of two metal electrodes placed in an electricity-conducting solution (Petrova-Koch, 2008). When exposed to light, electricity generation increased. The photovoltaic effect is the basis of solar cell technology. In 1870, the PV effect was initially studied in solids such as selenium (Kartikay et al., 2021). Czochralski method for obtaining pure Silicon crystal was developed within 1940 and early 1950. This method was utilized to produce crystalline Silicon solar cells with an efficiency of up to 11% (Kymakis & Amaratunga, 2003). At this time, PV effect ushered in a new era of solar power generation.

Figure 6 illustrate the principle of PV cell (Zhang & Yang, 2018). Sunlight is essentially composed of photons, discrete units of energy contained in light. PV cell is constructed from semiconductor materials and features a p-n junction. When solar radiation strikes a solar cell, some photons are absorbed, leading to the creation of electron-hole pairs in the cell. Upon constructing an external circuit, the voltage difference compels electrons to move from the n-side of the junction to the p-side (Zhang & Yang, 2018). Consequently, an electric current is generated in the external circuit.

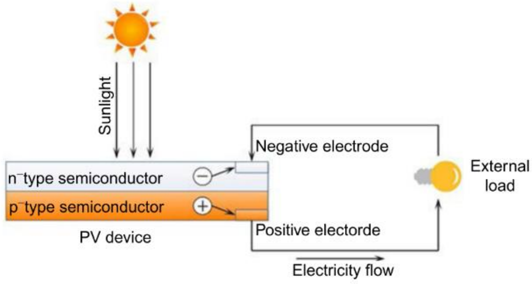

Figure 6. Principle Operation of a PV cell

RESULT AND DISCUSSION

Wavelength of Hex Code

By using Spectrometer application, the dominant wavelength of light can be measured. The table 2 shows the result of various hex code and its wavelength.

Table 3. Wavelength of Each Hex Code

Color	Hex Code	Wavelength (nm)
Light purple	#CE00FF	400
Purple	#8B00FE	450
Light blue	#00FEE4	500
Green	#33FF00	550
Orange	#FE9100	600
Red	#1B0000	650

The measurement of the wavelength using Spectrometer is in line with the theory of visible light spectrum. The wavelength of visible light is increasing from purple to red, ranging from 360nm to 760nm (Sliney, 2016).

At the quantum level, the fundamental particle of light, including visible light, is known as the photon (Prangnell, 2016). The photon has been shown to behave simultaneously as a particle and a wave; in quantum mechanics research, this is referred to as the counterintuitive wave-particle duality phenomenon (Salasnich, 2014). Moreover, the photon is an elementary particle in the boson category. The energy propagated by an electromagnetic wave, for all forms of electromagnetic radiation including visible light, is continuously distributed in the form of

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photons. The photon energy of visible light ranges from 2 to 2.75 electron volts (eV) (Lewerenz, 2012); the energy of a photon is inversely proportional to the wavelength of the electromagnetic wave.

Voltage and Current Output

Before measuring the voltage and current output from the solar cell, the light intensity of the phone's screen for each wavelength has been checked, and it shows 0.2 W/m². The distance from the phone's screen to the solar cell also needs to be the same; in this case, the distance is 15 cm.

The results of the measurements are shown in Table 4. Each wavelength exhibits different current and voltage outputs. The light with a wavelength of 400 nm has the highest recorded voltage and current, which are 1.75 V and 13.9 μA. Meanwhile, the light with the highest wavelength, 650 nm, has the lowest recorded voltage and current, which are 1.43 V and 8.7 μA.

Table 4. Current and Voltage Output

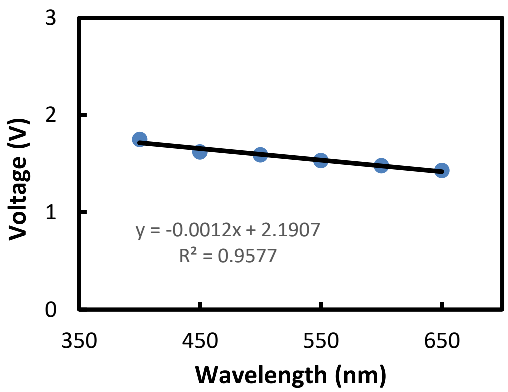
Wavelength (nm)	Voltage (V)	Current (μA)
400	1.75	13.9
450	1.62	11.4
500	1.59	10.2
550	1.53	9.8
600	1.48	9.4
650	1.43	8.7

Relationship Between Wavelength, Voltage, and Current

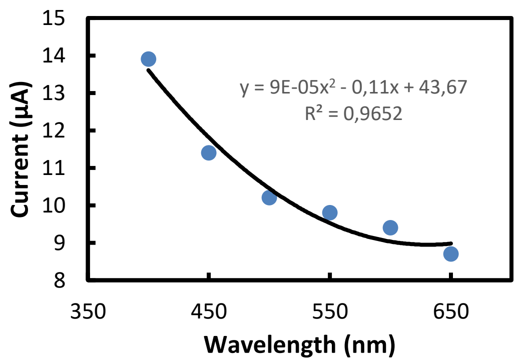
After the data was obtained, this study aimed to know the relationship between variables. The trendline of correlation graph between wavelength and voltage is shown in figure 7.

The analysis of the relationship between wavelength and voltage output in the solar cell reveals a quadratic correlation rather than a linear one. The fitting of the data produces a quadratic equation, indicating that voltage output does not decrease at a constant rate with increasing wavelength. Instead, the relationship is better represented by the equation $y = -0.0012x + 2.1907$, and the contribution of wavelength toward voltage output in solar cell is 95.7%. The R^2 value of 0.9577 suggests that wavelength has a strong effect on voltage output, contributing to 95.7% of the variance in voltage. The remaining 4.3% ($1 - R^2$) is likely due to other factors not accounted for in the experiment, such as minor inconsistencies in light intensity or distance.

The negative quadratic relationship aligns with theoretical principles in quantum mechanics. According to the photon energy-wavelength relationship, energy (and thus the potential voltage output in a solar cell) is inversely proportional to the wavelength of light; shorter wavelengths correspond to higher photon energies, which can excite more electrons and thus produce higher voltages. This experiment's quadratic fit mirrors this nonlinear relationship, as the rate of change in voltage decreases as the wavelength increases. This result is consistent with existing theoretical models for photon energy dependence in photovoltaic materials.



(a)



(b)

Figure 7. Correlation graph between wavelength and (a) voltage and (b) current

The analysis reveals that the relationship between wavelength and current output in the solar cell follows a quadratic pattern, not a simple linear trend. The best-fit equation for this relationship is $y = 9E\text{-}05x^2 - 0.11x + 43.67$, where the quadratic term captures the non-linear dependence of current on wavelength. This quadratic relationship indicates that the decrease in current with increasing wavelength is not constant but follows a curved trend. The R^2 value of 0.965 shows that wavelength accounts for 96.5% of the variation in current, with the remaining 3.5% likely due to external factors, such as minor variations in light intensity or distance.

This quadratic correlation is consistent with theoretical principles in photovoltaic energy conversion. According to quantum mechanics, photon energy, which is inversely related to wavelength, impacts the excitation of electrons in the solar cell material. Shorter wavelengths (with higher photon energy) are more efficient at generating electron flow, resulting in higher current outputs. As wavelength increases, the photon energy decreases, leading to a gradual reduction in current, reflected in the quadratic decline observed in this experiment. This nonlinear trend aligns with the photon energy-wavelength relationship and highlights how varying wavelengths impact current generation in photovoltaic materials.

Based on the previous study, there are many factors that can affect solar cell output. The most crucial factor is solar cell efficiency (Huang et al., 2013). The increased efficiency of solar energy technologies and reduced investment costs have significantly boosted the popularity of solar energy generation in recent years. PV panels are renowned for their direct conversion of solar radiation into electrical energy, featuring the major advantage of having no mechanical or moving parts (Isioma et al., 2021). However, they are susceptible to various environmental factors such as dust, dye, partial or total shading, and more. Among these factors, shading has the most substantial impact on PV panel efficiency. When dust, clouds, or other impediments cover the PV panels, their efficiency decreases (Brecl & Topič, 2011; Ghazi & Ip, 2014).

Solar cell also generally divided into three generation based on its material (Kibria et al., 2014). The first generation was based on wafer-based silicon cells, the second on thin-film technology, and the third on emerging technologies, including nano crystal-based, polymer-based, dye-sensitized, and perovskite-based solar cells (Parthiban & Ponnambalam, 2022). With different types of solar cells, the recommendation for future studies is to explore various generations of solar cells to compare their voltage and current outputs, especially in school experiment settings.

CONCLUSION

These laboratory activities are feasible for school implementation due to the accessibility and affordability of the tools and materials used. Through this study, the relationship between wavelength and the output of voltage and current in solar cells has been explored. The results indicate that both voltage and current outputs decrease with increasing wavelength, but this relationship follows a quadratic pattern rather than a linear one. Specifically, the quadratic equations derived for the voltage and current outputs show that as wavelength increases, the rate of decrease in both voltage and current slows, suggesting a non-constant rate of change.

This quadratic trend aligns with the theoretical principles of photon energy and wavelength in quantum mechanics. Higher-energy photons (shorter wavelengths) result in higher voltage and current outputs due to greater electron excitation in the solar cell. As the wavelength increases and photon energy decreases, voltage and current outputs decrease as well. However, the decrease follows a nonlinear pattern, as predicted by photon energy-wavelength relationships in photovoltaic materials. Future studies could investigate these effects across different types of solar cells to further explore how material and structural differences affect these relationships in educational settings.

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