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Didactic Resources

Using Grätzel cells as Arduino-controlled photosensors: proposals for the insertion of nanoscience and nanotechnology in classroom

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In this work, the production of Grätzel cells, also called dye-sensitized solar cells (DSSCs), their use as Arduino-controlled photosensors, and their application for the inclusion of nanoscience and nanotechnology in educational activities are reported. Grätzel cells were manufactured using titanium dioxide (TiO_2) nanoparticles, fluorine-doped tin oxide (FTO) coated glass, KI/I_2 solution, graphite, and grape juice as a sensitizer. Among the educational proposals suggested for the integrated use of DSSCs and Arduino, the assembly of a photometer for applications in optics and the construction of a light distance sensor stand out. As a suggestion for further studies, the UV-Vis spectra of titanium dioxide nanoparticles and grape juice were obtained and analyzed in order to illustrate how a deeper understanding of the materials used in DSSCs can provide answers about the mechanisms responsible for the detection properties of Grätzel cells in the context of the nanoscopic world.
Keywords: Dye-Sensitized Solar Cells, Arduino Board, Nanoscience and Nanotechnology, Physics Education.

1. Introduction

Nanoscience and nanotechnology will keep reinforcing the advance of automation, especially with strong contributions to the development of novel and more efficient types of sensors [1]. This is because nanoscale materials have numerous additional properties, such as new phase transitions, peculiar thermal and mechanical behavior, increased surface activity and reactivity, besides unusual optical, electrical and magnetic features [2]. Despite their importance, nanoscience and nanotechnology are still little explored in teaching activities, including university education. On the other hand, the use of Arduino boards in school projects has grown enormously in recent years, mainly due to their versatility, low cost, and simplicity [3]. Essentially, Arduino is an open-source platform consisting of a microcontroller and a C language-based software, which can interacts with external circuits, engines, loudspeakers, sensors, etc. [4, 5]. As it deals with electronics and programming, Arduino is strategic for integrated projects in STEM (Science, Technology, Engineering, and Mathematics). There are an immense number of sensors on the market that can be used in educational applications with Arduino. But for the vast majority of people, the nature of these devices and their principles of operation remain mysterious. In this scenario, the development of projects using Grätzel cells is proposed.

Grätzel cells, also called dye-sensitized solar cells (DSSCs), were developed by O'Regan and Grätzel in 1991 and have attracted a great deal of attention ever since due to their potential applications in solar panels [6]. Unlike conventional silicon-based solar cells, DSSCs do not require ultra-pure materials for their production, they can be mounted on flexible substrates (allowing applications in clothes, bags, car tops, etc.), and they can be applied to windows and doors, as they are not completely opaque [7]. In terms of its basic components, a classic DSSC consists of a photo-anode, a counter-electrode, and an electrolyte. The photo-anode can be constructed by depositing a thin layer of semiconductor material (TiO_2, Nb_2O_5, ZnO, SnO_2, etc.) on a conductive glass slide. In general, fluorine-doped tin oxide (FTO) or indium doped tin oxide (ITO) coated glass is employed for this function. To sensitize Grätzel cells, organic dyes can be used, which allow the absorption of visible light by the photocell. For the production of the counter electrode, it is possible to deposit on the conductive glass a thin layer of graphite, graphene, platinum, conductor polymers, etc. Finally, the electrolyte can be obtained, for example, by the stoichiometric mixture of potassium iodide (KI) and iodine (I_2) in some solvent, which leads to the formation of the I_3^-/I^- -redox pair [8]. Since DSSCs respond to light intensity, they can also be applied as photosensors. For educational applications with Arduino, the assembly of these photocells can be much more instructive than the simple use of a commercial sensor, since DSSCs allow students to build functional detection devices from minimally manufactured materials.

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Therefore, considering the potential uses of Arduino and the photosensitivity of Grätzel cells, as well as their constitution by nanomaterials, this paper proposes the integration of these two resources for the development of educational practices aimed at the insertion of nanoscience and nanotechnology in high school and in undergraduate education (mainly in physics, chemistry, engineering, and technology courses).

2. Materials and Methods

During the execution of the educational practices reported in this work, some alternatives for the production of Grätzel cells were tested. Among these, the methodology described below, which can be used as an initial guide, produced the best results. As a first step, fluorine-doped tin oxide (FTO) slides (50 mm ×50 mm ×2.2 mm) were cleaned in ultrasonic bath for one hour using the detergent Triton X-100. Then, the conductive glasses were rinsed and dried in a drying oven. These initial steps help the final efficiency of the DSSCs, but can be substituted by simple washing and natural drying if an ultrasonic bath and a drying oven are not available. For the preparation of the photo-anode layer, approximately 1.0 g of titanium dioxide (TiO_2) nanoparticles (purchased from Sigma-Aldrich) was mixed with isopropanol in an agate mortar and pestle set. Also to improve the final quality of the Grätzel cell, one drop of detergent (Triton X-100) and one drop of acetic acid (CH_3COOH) were added to prevent cracking of the TiO_2 layer. After the formation of a white paste, the mixture was applied on a FTO slide (on the conductive side) using a glass rod and a scotch tape to delimit the application area. The slide was then dried on a hot plate to remove the alcohol and promote the fixation of the TiO_2 nanoparticles on the conductive glass. After cooling to room temperature, the slide with TiO_2 was immersed for two hours in the dye to promote sensitization. To build the cathode, a thin layer of graphite was deposited on the conductive side of another FTO slide using a pencil. For the production of the electrolyte, a stoichiometric mixture of 0.5 moles of potassium iodide (KI) and 0.05 moles of iodine (I_2) was prepared using deionized water as solvent. Finally, after applying three drops of electrolyte solution on the graphite layer, the two prepared slides were joined to form the photocell. Figure 1 summarizes the described process. As discussed later, scientific investigations into the effect of different dyes, electrolytes and counter electrodes on the efficiency of solar cells were also carried out by the students who participated in the implementation of the educational practice.

For the applications of Grätzel cells as photosensors, an Arduino UNO board and basic electronic components, such as cables, resistors, LEDs, etc., were employed. To study the relationship between the Arduino average signal ($\bar{S}_A$) and light intensity (I), a commercial photometer and a DSSC were positioned at the same distance and angle in relation to a 12 volts-incandescent lamp, connected to a DC power supply. In a dark room, the voltage was changed from 7.5 V to 12.0 V (in 0.5 V steps), with the respective light intensity (in lux) and the Arduino average signal being measured after its stabilization. In particular, in the example where a DSSC was used as a distance sensor, the light source was a compact fluorescent lamp. In this practice, for calibration, the Arduino average signal ($\bar{S}_A$) was measured as a function of the distance d between the Grätzel cell and the light source. The data were plotted using a software for graphing/data analysis and a curve of $\bar{S}_A \times \frac{1}{d^2}$ was obtained. The data were curve-fitted (linear regression) and the parameters obtained were inserted in the code loaded in the Arduino, as shown later. With these steps, the Arduino IDE shows the distance between the dye-sensitized solar cell and the point light source (the same used for calibration). Since the drop in $\bar{S}_A$ is not instantaneous, it is necessary to take measurements at regular time intervals which must be identical to those used for calibration.

A commercial apparatus designed to study Malus' law was employed to test the sensitive properties of a Grätzel cell in experiments involving light polarization. This set possesses a polychromatic lantern, an iris, two polarizing filters, two converging lenses (4 di and 8 di), and a photometer. To study of the optical properties of the titanium dioxide nanoparticles and grape juice, an UV-Vis spectrometer (NOVA Instruments) was used.

3. Results and Discussion

3.1. Dyesensitized solar cells: operation principle

Let's start by discussing how a DSSC works. As summarized in Figure 2, light is absorbed by the organic dye, in which electrons are excited from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO). The electrons are then transferred to the semiconductor conduction band (CB). In this process, holes are created at the dye ground state, which can be filled by the electrons of electrolyte iodine ions (I^-), leading to the formation of I_3^- [9]. Therefore, photogenerated electrons can be transported in the semiconductor to the outer circuit, to the counter-electrode and, finally, to the electrolyte, where the I_3^- ions are converter into I^-, closing the cycle. In this process, the photon energy can be converted into useful work, which is the major function of a DSSC. Or, as proposed in this paper, one can use the electrical voltage produced to build a photosensor.

3.2. Getting started with DSSCs and Arduino

Now let's explore the use of dye-sensitized solar cells as sensors in applications with Arduino. For Grätzel cells produced according to the described methodology, the generated electric voltage reaches values up to ∼ 200

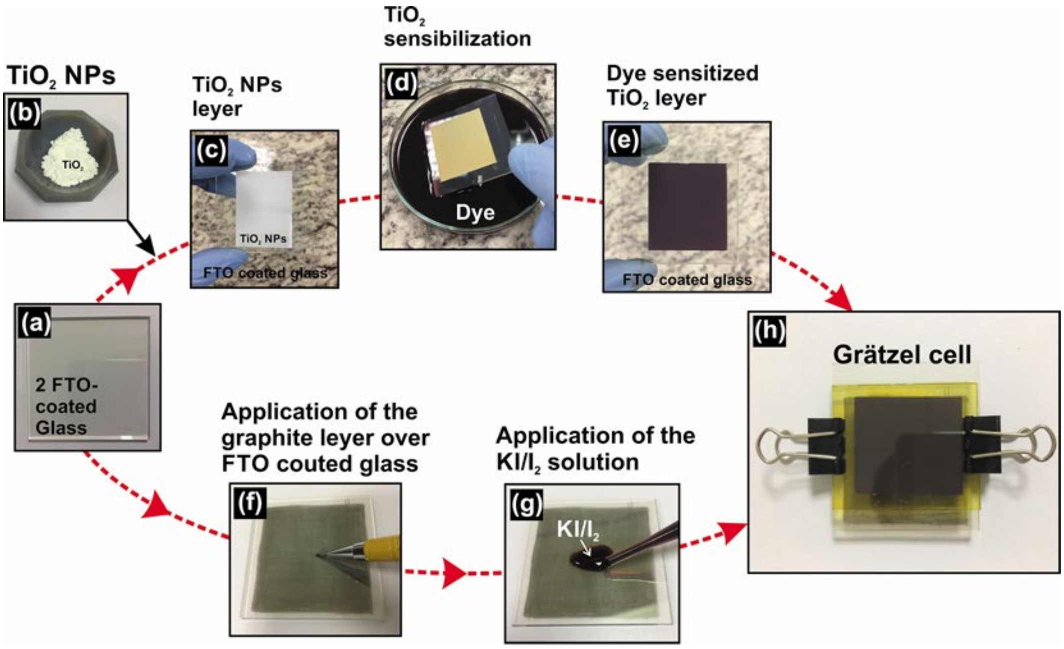

Figura 1: Schematic showing the process of assembling a Grätzel cell. In (a) is shown the FTO-glass, which is coated with a thin layer of TiO_2 nanoparticles (b) to form what is displayed in (c). In (d), one can see the sensitization of the TiO_2 nanoparticles with organic dye and in (e) the final result after washing and drying. In (f), a second FTO-glass is covered with a layer of graphite and in (g) the electrolyte is applied. In (h), a finished DSSC is shown.

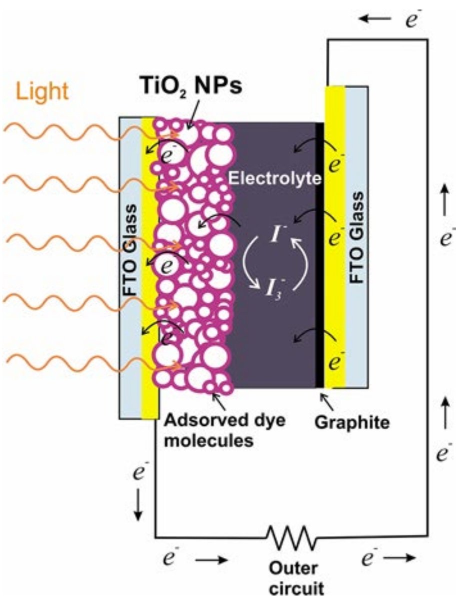

Figura 2: Diagram showing the working principle of a DSSC. The incident light passes through the conductive glass, reaching the dye and exciting its electrons to the semiconductor conduction band. These electrons are transported by the semiconductor to the outer circuit (represented by the electrical resistance), reaching the counter electrode, where the I_3^- ions are converted into $3I^-$.

mV. The most basic way to explore this property with Arduino is to simply read the voltage, which can be done by connecting the DSSC photo-anode to the Arduino ground (GND) and the cathode to an analog input (such as A0, for example). Since the Arduino board contains a 10-bit analog-to-digital converter, it can read input voltages between 0.0 and 5.0 volts and map them as integers between 0 to 1023. Thus, the values read by the board must be multiplied by 5.0/1023 to provide the results in volts (V). Through the assembly described and with the required code (included in the supplementary material of this paper), the measured voltage values can be displayed on the "Monitor Terminal" of the Arduino IDE (Integrated Development Environment).

This first example highlights the potential of dye-sensitized solar cells to produce light-dependent voltage and the Arduino's versatility to function as an electrical meter. In addition, it is possible to discuss the capacity to harness solar energy based on the use of Grätzel cells. In order to employ the DSSCs as photosensors, an essential strategy is to smooth out the signal read by the Arduino. This can be accomplished by repeatedly reading the signal from an analog input and calculating its average. Details regarding the implementation of this step, which significantly reduce the noise/signal ratio, can be obtained in the supplementary material of this paper. For a more practical application of the light-sensing properties of the DSSCs, one can use the voltage read by the sensor to turn a light-emitting diode (LED) on or off. For this application, a resistor and an LED must be connected in series between a digital pin and the Arduino GND. The supplementary material in this paper provides further instructions, including the additional lines of code required for LED lighting experiment. To turn a higher wattage lamp on or off using a DSSC and an Arduino, a relay is required, as described in Ref. [10].

3.3. Studying Malus' law with DSSCs and Arduino boards

An interesting application from the point of view of physics teaching is to transform a Grätzel cell into a photometer and explore its properties in optical experiments focused on the study of light intensity. This is possible because the signal read by the Arduino (S_A), or its average ($\bar{S}_A$), is directly proportional to the light intensity (I) reaching the functional surface of the DSSC, as can be seen in Figure 3, whose experimental data were obtained using a Grätzel cell and a commercial photometer. Therefore, one can use this approach to study, for example, Malus' law. Malus' law, which can be employed to demonstrate the electromagnetic wave nature of light [11], considers a linearly polarized light beam incident upon a linear polarizer at an angle θ. As the observed intensity is proportional to the amplitude of the electric field, the light intensity after passing through the polarizing filter will be [12]:

$$I = I_0 cos^2\theta \tag{1}$$

where I_0 is the intensity of light before it passes through the polarizer. Since the average voltage measured by the Arduino $\left(\bar{S}_A\right)$ is proportional to the luminous intensity $\left(\bar{S}_A \propto I\right)$, then $\bar{S}_A \propto cos^2\theta$. Thus, by connecting the Grätzel cell to the GND and A0 pins of the Arduino board and measuring $\bar{S}_A$ as a function of θ, Malus' law can be studied experimentally. As the focus of this work is on the sensory properties of dye-sensitized solar cells and not on the polarization phenomena itself, a commercial didactic set was used to test the functionalities of the photocells. In this experiment, the light produced by a polychromatic lantern (S) passes through an iris (I), the first polarizing filter (P), two converging lenses (L_1 and L_2), a second polarizer that acts as an analyzer (A), and finally reaches the DSSC (D). As can be seen in Figure 4, the average normalized signal measured by the Arduino $\left(\bar{S}_A\right)$ and the normalized light intensity captured by a commercial photometer clearly show cosine-squared dependence with θ, in addition to providing data with similar quality. In fact, as shown in the inset in Figure 4, the graph of $\bar{S}_A$ as a function of $cos^2\theta$ is suitably linear, as expected. Therefore, Grätzel cells can be employed perfectly as photometers in light polarization experiments.

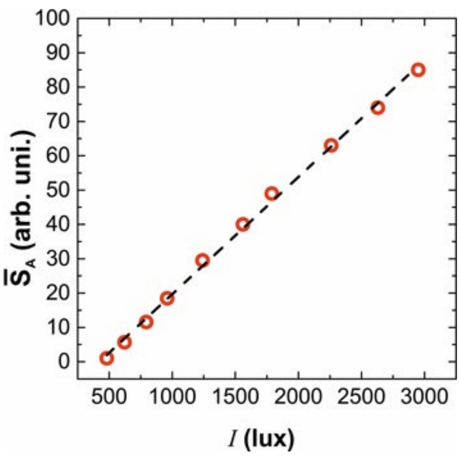

Figura 3: The Arduino average signal $\bar{S}_A$ (in arbitrary units) plotted against the light intensity I (in lux), measured using a commercial photometer.

3.4. Making a light distance sensor

Another photometric application of DSSC cells and Arduino is to measure the light intensity (or $\bar{S}_A$) as a function of the distance (d) between the photocell and a lamp. Figure 5 shows a schematic of how the measurement can be performed and Figure 6 displays the experimental results obtained. As presented in Figure 6, it can be seen that $\bar{S}_A$ is inversely proportional to the square of the distance $\left(\frac{1}{d^2}\right)$, as expected for a point light source. This result, by itself, allows the execution of didactic activities in optics aiming at the study of light intensity and the inverse square law. However, the

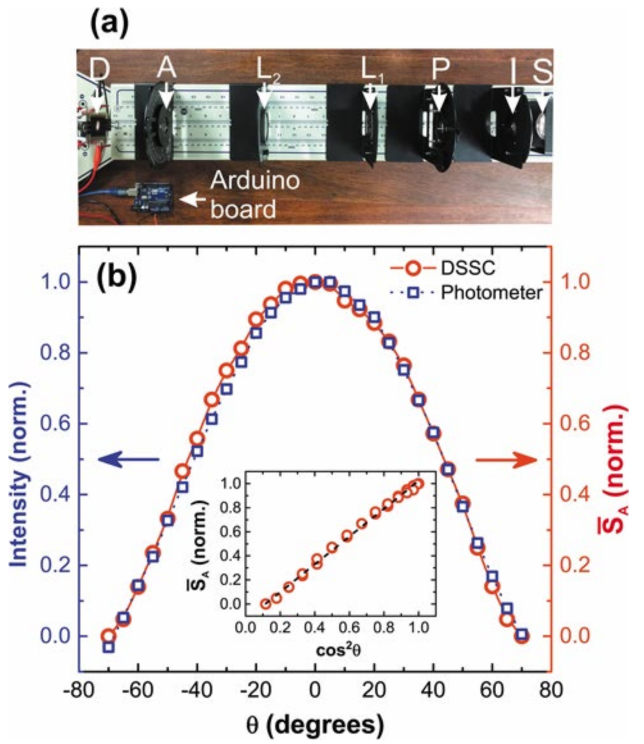

Figura 4: (a) Experimental apparatus for studying Malus' law. The labels in this picture represent polychromatic light source (S), iris (I), polarizer (P), first converging lens (L_1), second converging lens (L_2), analyzer (A), and DSSC (D). (b) Intensity (normalized) measured by the commercial photometer and Arduino average signal $\bar{S}_A$ (normalized) plotted against θ (angle between the polarizer axis and the direction of light polarization). In the inset, $\bar{S}_A$ are presented in terms of $cos^2\theta$.

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Arduino offers an interesting way to go further: it can be programmed to provide the distance between the DSSC and the light source. The following code can accomplish this task:

```
int i;
float Average_S_A, S_A, N, Distance,
alpha_0, alpha_1;
void setup() {
Serial.begin(9600);
analogReference(INTERNAL);
N=100;
//Change the alpha_0 and alpha_1 values
according to your linear fitting;
alpha_0=270;
alpha_1=-1.0791;
}

void loop() {

Average_S_A=0;
for(i=1;i<N;i++)
{
S_A=analogRead(A0);
Average_S_A = Average_S_A+S_A;
}
{
Average_S_A=Average_S_A/N;
Distance=sqrt(alpha_0/(Average_S_A
-alpha_1));
}
if (Distance>= 15){
Serial.println("More than 15 cm");
//Change the "15 cm" (above) for a value
according with your experiment;
}
else if(Distance<=3){
Serial.println("Less than 3 cm");
//Change the "3 cm"  (above) for a value
according with your experiment;
}
else {
Serial.println("");
Serial.print(Distance);
}
}
```

As the Arduino average signal $\bar{S}_A$ can be modeled by $\bar{S}_A = \frac{\alpha_0}{d^2} + \alpha_1$, where α_0 and $\alpha_1$are constants, isolating the distance in this equation $\left(d = \sqrt{\frac{\alpha_0}{\bar{S}_A - \alpha_1}}\right)$ and using the linearization result obtained from Figure 6 to find α_0 and α_1[1], the d values can be easily given on the Arduino IDE Monitor Serial. In the displayed code, an "if-else" statement is also used, since for distances up to 3 cm, the experimental points do not follow the inverse square law and for large distances (greater than 15 cm)[2], $\bar{S}_A$ is too low to provide the resolution needed for reliable results to be displayed. Thus, this simple example is of great value to demonstrate how minimally manufactured materials (TiO_2 nanoparticles, grape juice, FTO glass, KI/I_2 solution, etc.) and an Arduino board can be joined to form a device that provides real-time information about a given physical quantity.

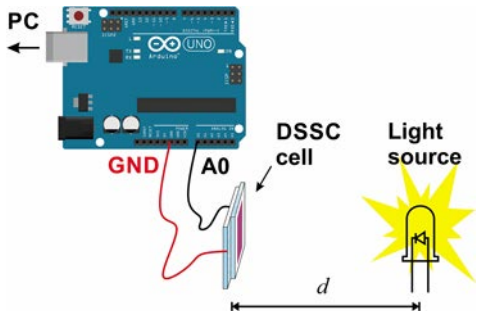

Figura 5: Assembly diagram used to integrate Arduino board and DSSCs. Part of this image (Arduino) was obtained by means of Fritzing software [14].

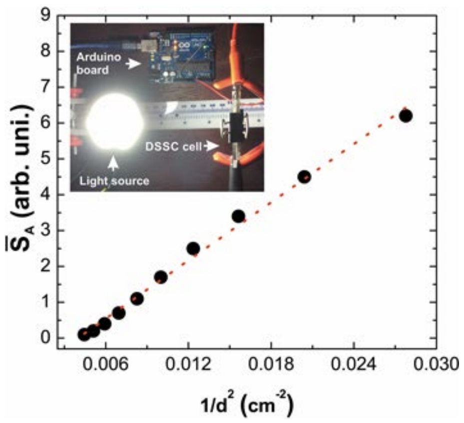

Figura 6: Average Arduino signal $\bar{S}_A$ (arbitrary units) as a function of $\frac{1}{d^2}$. Inset shows the assembly used to explore the relationship between light intensity and distance from the light source.

3.5. Going further: exploring the optical properties of TiO_2 and grape juice (dye) in the context of nanoscience and nanotechnology

In advanced projects involving Grätzel cells, Arduino, and nanotechnology, one of the key topics to be explored is the properties of semiconductor material. Semiconductors are the basis of today's electronic technology, which

[1] The values of α_0 and α_1 can be obtained using a graphics plotting software, such as QtiPlot, which is free [13]. For this task, $\bar{S}_A$ is plotted against $\frac{1}{d^2}$ and a linear regression is performed. The slope coefficient will be α_0 and the linear coefficient will be α_1. For the Grätzel cell used by the author in this example, $\alpha_0 = 270$ and $\alpha_1 = -1.0791$.

[2] These values may be different for the reader-mounted Grätzel cells.

can be defined as materials with electrical resistivity in the range of $10^{-2} - 10^{9}\Omega\times$cm. In other words, semiconductors are materials with intermediate electrical conductivity between conductors and insulators. By far, the best-known semiconductor is silicon (Si), but there are many others, such as germanium (Ge), gallium arsenide (GaAs), zinc oxide (ZnO), lead sulfide (PbS), titanium dioxide (TiO_2), etc [15]. To understand the basics of semiconductors, it is necessary to keep in mind some ideas of band theory of solids. The microscopic behavior of electrons in a solid can be described in terms of electronic band structure. In a semiconductor, for the production of electric current, electrons must receive enough energy to be promoted from the so-called valence band (VB) to the conduction band (CB). In this process, they need to break through an energy barrier called energy gap or band gap (E_g). The size of this gap is of fundamental importance for the properties of semiconductor. For DSSC applications, wide band gap semiconductors, such as TiO_2, ZnO, Nb_2O_5 or SnO, have been used as photo-anode. The photo-anode performs two functions: it is the support for the sensitizer and photoexcited electron carrier for the external circuit. [16]. The inclusion of these themes in activities aimed at physics and chemistry teaching can be widely explored, especially considering the properties of semiconductors and dyes. As an example, one can focus on the optical absorption process of these materials to explore the concepts of light absorption, energy levels, band theory, etc. Figure 7 shows the UV-Vis absorption spectra of TiO_2 and grape juice (dye). As can be seen, titanium dioxide has low optical absorption in the visible range. However, for photons with wavelength below ~400 nm (ultraviolet-UV region), its absorbance is high. This is because TiO_2 presents wide band gap, around 3.2 eV [17]. Consequently, only photons with energy greater than ~ 3.2 eV can excite electrons from the valence band to the conduction band. Therefore, visible light is poorly absorbed, so it is necessary to employ a substance to absorb the light energy and convert it into electric current. For this reason, dyes are essential in DSSCs.

The contribution of the dye can be seen clearly in Figure 7, where the absorption spectrum of grape (*Vitis labrusca L.*) juice is shown. Grape juice presents a spectrum with high absorbance in the UV-region and shows a characteristic broad peak at approximately 530 nm [18]. The profile of the described spectrum is due to the presence of anthocyanins, which are pigments found in fruits such as grapes. For the production of highly efficient DSSCs, the sensitizers must anchor on the surface of the electrode nanoparticles with their carboxylate or phosphonate group, allowing the injection of electrons into semiconductor CB [19], as shown in Figure 7 for TiO_2 and anthocyanin. The use of nanoparticle semiconductor materials maximizes their relative surface area, increasing the adsorption of dye molecules [7]. Therefore, the adoption of nanomaterials in Grätzel cells is essential for their efficiency.

In this work, many other organic dyes, such as sugar beet (*Beta vulgaris esculenta*), chlorophyll extracts, açaí berry (*Euterpe oleracea Mart.*), turmeric (*Curcuma longa L.*), and annatto (*Bixa orellana*) were tested. However, the best results (color fixation, staining time, and voltage produced) were obtained with commercial grape juice (pure juice, without additives). Other organic sensitizers may be used for educational applications depending on local availability. However, it is desirable to use dyes that absorb as much of incident light as possible, from the visible to the near-infrared. These considerations can be discussed with students in the light of the absorption spectra shown in Figure 7. In terms of the spectroscopy results, for high school projects, where a commercial UV-Vis spectrometer is probable not available, dyes absorption spectra can be obtained using a low-cost webcam-based spectrometer [20, 21].

3.6. Expected educational outcomes and brief comment on the implemented practice

STEM projects help students develop essential skills that allow them to acquire scientific information and think scientifically. Considering the integration of the areas described in this work, it is expected that participation in these activities will encourage students to ask questions, such as: (1) What is the working principle of the dye-sensitized solar cells? (2) Why are semiconductors so important in Grätzel cells? (3) What are nanomaterials and what is their role in the efficiency of these cells? (4) Why can a substance in daily use, such as fruit juice, be used to convert solar energy into electrical voltage? (5) What physical quantities can be measured by Arduino and how to use them to perform useful tasks? Additionally, projects with these themes can allow students to seek answers and formulate hypotheses for these questions using scientific research methods, also permitting: (i) to study the nature of the materials used in Grätzel cells (TiO_2 nanoparticles, FTO coated glass, organic

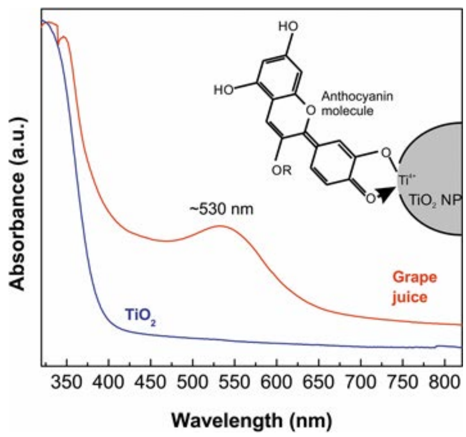

Figura 7: UV-Vis spectra of TiO_2 and grape juice. Absorbance is plotted in arbitrary units. The image represents the process of anchoring the anthocyanin molecule in a TiO_2 nanoparticle [10].

dyes, electrolytes, etc.); (ii) investigate which are the best dyes to maximize the efficiency of DSSCs; (iii) to propose changes in nature, quantity and concentration of the electrolyte solution used; (iv) research what are the best types of counter electrodes for DSSCs, considering the resources available. The integrated use of Grätzel cells and Arduino boards in the educational environment also allows solving problems related to the production of photosensors to study physical principles and how to apply the knowledge acquired to propose new technologies. In the process, students need to develop programming, math and engineering skills to solve real problems. Finally, it is possible to communicate the results obtained through reports, scientific papers, presentation, etc. Therefore, the expected outcomes for projects involving the themes described in this work enable the development of skills related to formulation of questions, investigation, hypothesis creation, problem-solving, and scientific communication. Students are also expected to learn basic concepts about nanomaterials, chemical reactions, band theory, interaction between radiation and matter, UV-Vis spectroscopy, programming, electrical circuits, etc.

The practice described in this work was applied to undergraduate students in Physics and Industrial Automation Technology at the Instituto Federal de Brasília (Federal Institute of Brasília, Brasília-Brazil), in 2019. The team was formed by five students and the entire project was carried out over an entire semester. The study aimed to analyze the feasibility of producing photosensors based on Grätzel cells for use in Arduino boards. Initially, students did a bibliographic search to understand the basic principles of dye-sensitized solar cells and how to build them. They also proposed carrying out studies to test different types of dyes (sugar beet, chlorophyll extracts, açaí berry, turmeric, annatto, and grape juice), electrolytes (KI/I_2-solution with different proportions), and counter electrodes (pencil scratches, application of candle soot or graphite spray) to ensure the highest efficiency of Grätzel cells. All these possibilities were tested and the best results found are in accordance with what is described in the section "Materials and methods". The students formulated hypotheses about the absorption properties of TiO_2 and dyes, in addition to performing UV-Vis spectroscopy measurements to confirm their predictions. They also developed the basic skills to integrating DSSCs with Arduino boards, including the assembly of basic electrical circuits and the required programming. Finally, the students presented the results obtained and the prototypes built at regional scientific conferences. For these communications, they had to select the information based on the results found and develop appropriate explanations for different types of audiences. In the students' perception, the activity was very stimulating and enriching, contributing to their insertion in the world of nanoscience and nanotechnology[3].

4. Conclusion

The results presented show that the Grätzel cells manufactured according to the described methodology can be fully integrated into didactic applications with Arduino microcontrollers. In terms of their production, DSSCs are easily assembled using TiO_2 nanoparticles, organic dyes, FTO-coated glass slides, KI/I_2 solution, and graphite. In particular, it has been demonstrated that Grätzel cells can be applied satisfactorily as photometers and included in studies involving optics, especially in experiments covering Malus' law and the inverse-square law. Additionally, Arduino features allow the construction of a device to provide real-time information about the distance between the DSSC and a light source, which can be valuable for STEM applications. On the other hand, with UV-Vis spectroscopy it is possible to explore the absorption properties of semiconductors and organic dyes, reinforcing the role of sensitizers in DSSCs, as well as highlighting the effects of the reduced dimensions of nanoparticles on the anchoring of dye molecules, among other considerations. Therefore, it can be concluded that the construction of functional photosensors from minimally manufactured materials produces exceptional conditions for the development of multidisciplinary nanoscience and nanotechnology projects.

4.1. Potential hazards and safety precautions

Although assembly and application of DSSCs involve harmless processes, chemicals must be handled with care. In addition, during construction, instructors and students must wear gloves, glasses, and protective clothing. All laboratory safety rules and precautions described on product packaging must be strictly followed.

5. Acknowledgments

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6. Supplementary material

The following online material is available for this article:
Examples 1, 2 and 3.

[3] Details on students' opinions regarding their participation in this project are provided in the supplementary material in this paper.

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