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Nanotoxicity in Physics Education: Electrochemical Synthesis of Carbon Dots and Their Effects on Mung Beans

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Abstract

This study introduces the toxicity of nanomaterials through a practical and accessible experiment. An electrochemical approach was employed to synthesize carbon dots (CDs) from graphite rods extracted from recycled batteries. The impact of CDs solutions on the growth of mung bean sprouts was then investigated as a representative model for nanotoxicity assessment. The results revealed significant differences in growth and development between control samples and those exposed to CDs. To evaluate the educational impact, an experiment was carried out with 25 undergraduate students divided into five groups. The activity helped students better understand the properties and risks of nanomaterials, while also developing their skills in data analysis and teamwork. Three surveys conducted before and after the lecture and experiment showed that students improved their knowledge of nanotechnology and their practical skills. This interdisciplinary experiment, integrating physics, chemistry, and biology, aligns with the Vietnamese Grade 10 Specialized Physics Study Module and undergraduate nanomaterial courses. Using recycled materials promotes sustainable practices and helps students connect theoretical knowledge with real-world applications, making learning more engaging and meaningful. It also provides a hands-on model for integrating nanoscience into STEM education in an accessible and practical way.

Keywords: Nanotoxicity, carbon nanoparticles, mung beans.

INTRODUCTION

The field of nanomaterials has impacted all aspects of everyday life since Professor Norio Taniguchi first used the word "nanotechnology" in 1974 (S. Srivastava, Bhargava, Srivastava, & Bhargava, 2022). Nanomaterials, which have at least one dimension smaller than 100 nm, often have unique properties that are different from larger-scale materials (Asha & Narain, 2020). With advancements in manufacturing techniques, researchers can now create and study nanoscale structures in greater detail, discovering new characteristics that do not exist in bulk materials (Asha & Narain, 2020; Lee & Bent, 2020). These materials are widely used in areas such as electronics, medicine, energy, and environmental protection (Hwang et al., 2022; Saleem, Zaidi, Ismail, & Goh, 2022; Stanford, Rack, & Jariwala, 2018; Yao, Zhang, Orgiu, & Samorì, 2019). Advances in nanotechnology have also paved the way for next-generation materials with improved mechanical, optical, and catalytic properties, making them indispensable in various industrial and biomedical applications. For example, nanomaterials improve sunscreens by offering better UV protection and enhance water purification systems by helping to remove pollutants more effectively, ensuring cleaner drinking water (Kumar, 2023; Singha, Maity, & Pandit, 2020; Tlili & Alkanhal, 2019).

Despite the remarkable advancements in nanomaterial development and their widespread applications, growing concerns have emerged regarding their potential risks to human health and the environment (Fiordaliso, Bigini, Salmona, & Diomede, 2022; Forest, 2021; Joksimovic et al., 2022; Pérez-Hernández et al., 2021). These concerns arise due to the small size and high surface reactivity of nanoparticles, which enable them to interact with biological systems at the cellular and molecular levels. Numerous studies have pointed out that while nanoparticles offer great benefits, their interaction with biological systems remains a subject of extensive investigation, particularly regarding their potential accumulation in tissues and long-term effects on human health. Zhang et al. demonstrated that oral exposure to titanium dioxide nanoparticles (TiO_2NPs) altered the diversity of the gut microbiota in mice, leading to reduced locomotor activity. Their findings suggest that TiO_2NPs may influence the gut-brain axis through nerve signalling pathways, although no significant inflammation or cognitive impairment was observed (S. Zhang et al., 2020). Similarly, Joksimovic et al. (2022) highlighted the risks associated with nanoplastics, which, due to their microscopic size, can infiltrate marine organisms, obstruct their digestive and respiratory systems, and act as carriers of harmful pollutants. As these particles accumulate in the food chain, they pose potential health risks, including oxidative stress, inflammation, and metabolic disruptions in humans (Joksimovic et al., 2022). Moreover, Srivastava & Choubey investigated the toxicity of silver-engineered nanoparticles (Ag-ENPs) on various biological systems, including bacteria, mammals, and plants. Their findings indicate that Ag-ENPs exert toxic effects due to their strong affinity for cellular thiol groups. However, when biosynthesized using *Veronica officinalis* extract, these nanoparticles exhibited no toxicity, demonstrating that synthesis methods influence nanoparticle safety profiles. (V. Srivastava & Choubey, 2019). Such findings emphasize the importance of evaluating the potential ecological and health implications of nanomaterials before their large-scale implementation.

Given these concerns, it is crucial to integrate nanotoxicity studies into educational curricula to enhance students' awareness of both the advantages and potential risks associated with nanomaterials. Hands-on experiences can help bridge the gap between theoretical knowledge and practical implications, allowing students to critically evaluate both the benefits and risks of nanotechnology. An example is the study by Ross et al. (2016), in which undergraduate students assessed the phytotoxicity of engineered nanomaterials using mung beans (Ross, Owen, Pedersen, Liu, & Miller, 2016). When exposing mung beans to solutions containing silicon dioxide (SiO_2) and zinc oxide (ZnO) nanoparticles, the students observed distinct toxic effects, with ZnO nanoparticles significantly inhibiting plant growth at a concentration of 20 mg/L. The experiment provided both qualitative and quantitative data, allowing students to directly measure and analyze nanotoxic effects. These hands-on activities reinforce the concept of nanophytotoxicity and equip students with essential skills to evaluate the environmental impact of nanomaterials. However, in this study, students used pre-prepared nanoparticle solutions rather than synthesizing the nanomaterials themselves. Although this approach ensured safety and experimental consistency, it limited students' exposure to the complete process of nanomaterial synthesis and toxicological assessment. To address this limitation, experimental models are needed that allow students to actively participate in both the synthesis and toxicity evaluation of nanomaterials, thereby providing a more holistic understanding of their properties and potential risks.

Through a review of literature, we identified a relatively simple electrochemical approach for synthesizing nanomaterials, specifically carbon dots, that can be conducted by undergraduate or even high school students. In this method, Ming et al. utilized a static potential applied to two graphite rods, causing carbon to corrode from the anode under continuous stirring in ultrapure water for 120 hours (Quang, 2024). To improve upon this method, we employed a commercial saline solution (Thien An Co., Ltd, Vietnam) as the electrolyte, significantly reducing the reaction time from 120 hours to just 6 hours (Quang, 2024). This modification not only enhances the efficiency of the synthesis but also introduces students to the concept of optimizing experimental parameters for real-world applications. Additionally, rather than using commercial graphite rods, we utilized recycled battery graphite rods as both a sustainable alternative and an educational tool to introduce students to the concept of environmentally conscious research practices.

In this context, we selected carbon dots (CDs) as the model nanomaterial for synthesis, while mung bean sprouts were employed to assess nanotoxicity. Following previous research, we synthesized CDs from graphite rods obtained from recycled batteries (Quang, 2024). We then experimented to evaluate the impact of CDs solutions on the growth of bean sprouts, serving as an example of nanotoxicity assessment. To evaluate its educational effectiveness, the experiment was implemented with undergraduate students. This hands-on activity aligns with the Vietnamese Grade 10 Specialized Physics Study Module, enabling teachers to guide students in synthesizing CDs using recycled materials and evaluating their effects on mung bean growth. It reinforces physics concepts, such as electrochemical synthesis, while connecting theory to practice. In addition, the experiment promotes sustainable practices through the use of recycled materials and serves as a model for integrating nanoscience into STEM education by connecting physics, chemistry, and biology (Erol & Demir, 2024). Beyond high school, it can also be adapted for university nanomaterial courses, encouraging students to explore the benefits and risks of nanotechnology while fostering environmental awareness.

METHOD

For the preparation of CDs, we followed the steps presented in previous studies, as shown in Figure 1 (Quang, 2024):

1) Extract two graphite rods from the recycled battery core (Figure 1 (a)).

2) Position two graphite rods parallel to each other in 10 ml of saline solution (0.9% NaCl) mixed with 80 ml of distilled water. After 6 hours of vigorous magnetic stirring under the influence of a direct current (DC) supplied by two 9-volt batteries connected in series, the anode graphite rod underwent corrosion (Figure 1 (c)). During this process, a dark colouration gradually developed, as illustrated in Figure 1 (d). This colour change serves as a visual indicator of the ongoing electrochemical reaction, providing students with direct observations of the corrosion of carbon from the anode graphite rod. In the previous publication, we used a saline solution (0.9% NaCl) as it is for the electrolyte solution (Quang, 2024). However, in the context of the nanotoxicity experiment, we should also use an electrolyte solution for the mung beans grown with the control sample. However, mung beans grown in 0.9% NaCl saline solution showed severe growth stunting. To minimize the effect of NaCl on the control sample, we deliberately diluted the saline solution at a 1:8 ratio (1 part saline solution to 8 parts distilled water). This dilution was also applied as the electrolyte solution to fabricate CDs via the electrochemical approach.

3) Intensive magnetic stirring for 6 hours under an applied DC voltage of 18 V resulted in the gradual appearance of a dark colour.

4) The solution was finally purified through a 0.22 μm filter and used for nanotoxicity.

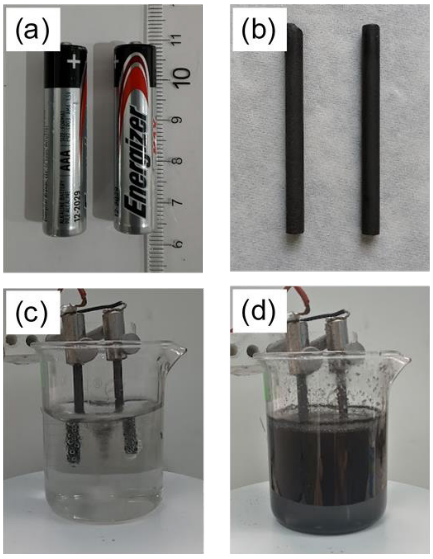

Figure 1. (a) Photograph of an AA-size battery, (b) Two graphite rods extracted from the battery core, (c) Intensive magnetic stirring during the electrochemical process, and (d) Photograph of the obtained CD solution after 6 hours of stirring

To determine the concentration of CDs in the obtained solution, we conducted the following steps: First, a five-digit balance was used to measure the mass m_1 of an empty test tube. Next, 2 ml of the CDs solution was added to the test tube, which was then placed in an oven for drying. After drying, the test tube was reweighed using the same five-digit balance to obtain the mass m_2. The CDs concentration was calculated using the formula $(m_2-m_1)/2ml$, yielding an estimated concentration of 5.38 mg/ml. This procedure enables students to prepare CDs at various concentrations as needed. The steps for determining CDs concentration are illustrated in Figure 2.

Next, to demonstrate the toxicity of nanomaterials, mung bean sprouts were chosen for investigation due to their short growth cycle and suitability for water-based cultivation (M. Zhang et al., 2018). To minimize variations in experimental results, mung beans with a uniform appearance and size were deliberately selected after being purchased from the local market. The selected mung beans were thoroughly cleaned with distilled water and arranged in 8 Petri dishes, with 15 seeds per dish, for the culture process. Over a period of five days, 10 ml of solution containing different concentrations of CDs (0.1×, 0.2×, 0.3×, 0.5×, 0.8×, 1× = 5.38 mg/ml) was added daily to each Petri dish to support the growth of the mung beans. To maintain controlled experimental conditions, all Petri dishes were placed in an environment with stable temperature and light exposure, minimizing the impact of external factors on seed germination. The length of the sprouts was measured daily using ImageJ software, as explained below, providing quantitative data on the growth process at different nanoparticle concentrations.

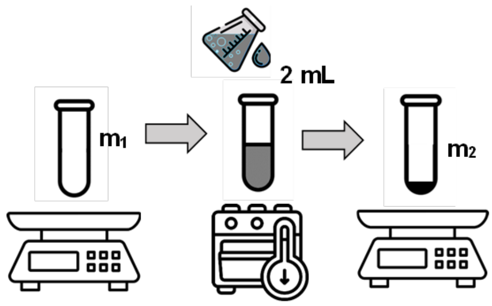

Figure 2. The procedure for determining CDs' concentration

RESULT AND DISCUSSION

1. Characterization and nanotoxicity assessment

After establishing the fabrication, we briefly characterized the properties of the obtained CDs. The supplementary information file provides Figures 1SI and 2SI, showing the transmission electron microscopy (TEM) image and X-ray diffraction (XRD) pattern of the synthesized CDs, respectively. Educators can refer to these materials for a deeper understanding. However, these advanced analytical methods can be challenging for high school students, who often lack the foundational knowledge and skills to apply such techniques. Fortunately, CDs exhibit a distinctive optical property- excitation-dependent photoluminescence, where the emission colour changes with the excitation wavelength, observable without specialized equipment (Quang, 2022). We utilize this feature to demonstrate the presence of CDs in the solution, making it accessible to learners without relying on complex instruments. Specifically, we illuminated the sample using laser pointers at 405 nm and 532 nm wavelengths. As shown in Figure 3, the solution emits a 'yellow-orange' colour under the 405 nm laser, while a 'deep red' colour appears under the 532 nm green laser. Although the intense green light partially obscures the 'deep red' emission, careful observation still reveals a clear red shift. For a detailed analysis of fluorescence wavelengths and their colours, instructors may consult our previous work (Quang, 2024).

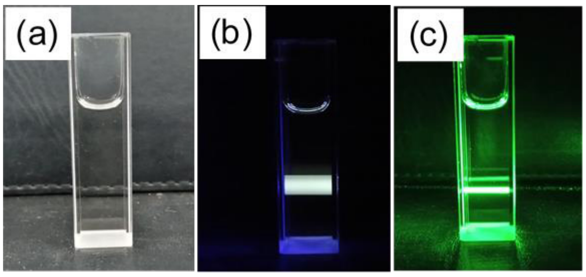

Figure 3. Photographs of the obtained CDs solution under room light (a), 405 nm excitation (b), and 532 nm excitation (c)

After verifying the characteristics of CDs, we studied their effects on the growth of the mung bean. Photographs of the mung beans in the dishes over time are presented in Figure 4. The length of the bean sprouts can be roughly estimated using the yellow (or orange) sticker with dimensions of 2.1 cm × 1.2 cm. On the fifth day, after photographing the bean sprouts in the Petri dishes, we carefully arranged the plants treated with different doses of CDs to visually demonstrate the effects of nanotoxicity, as shown in Figure 5. Two specimens were also prepared as control samples. First, the beans were grown in a medium containing only distilled water (dH_2O group). Second, the beans were cultured in a solution containing diluted saline solution (one part saline solution to eight parts distilled water, Non-dH_2O group). All bean sprouts were grown under the same conditions.

We used ImageJ software and a ruler to measure the length of mung bean sprouts. To provide a reference for calibration, a ruler was placed next to the sprouts in each Petri dish before taking photos. Images were captured daily over five days using a mobile phone, maintaining a fixed angle and distance to ensure consistency under natural lighting. In ImageJ, the Straight Line tool was used to draw a line along a known length of the ruler, followed by setting the scale using the Set Scale function, where the actual length was entered in centimeters (cm). Once calibrated, each sprout was measured from its base to the tip, with adjustments made for curved sprouts when necessary. To improve accuracy, each measurement was taken multiple times, and the average value was recorded.

After establishing the measurement scale in ImageJ, we proceeded with analyzing the effect of CDs on the growth of the mung bean over the five days. Figure 6 illustrates the toxicity of CDs, evaluated after five days of incubation of bean sprouts with different doses. Each bar in the graph represents the mean and standard deviation values. As shown in Figure 6, there is a noticeable discrepancy in the growth and development of bean sprouts between the control samples and those treated with CDs solutions. Notably, low concentrations of CDs solution enhanced sprout development, whereas higher doses inhibited it. The length of the mung bean plants was considerably greater than that observed in the absence of CDs (dH_2O group). At a concentration of 0.1×, CDs exhibited remarkable efficiency in promoting sprout growth. However, increasing the dose to 1× negatively impacted the growth of the beans, exhibiting toxic effects. Interestingly, we also observed that the non-dH_2O group showed better growth compared to the dH_2O group.

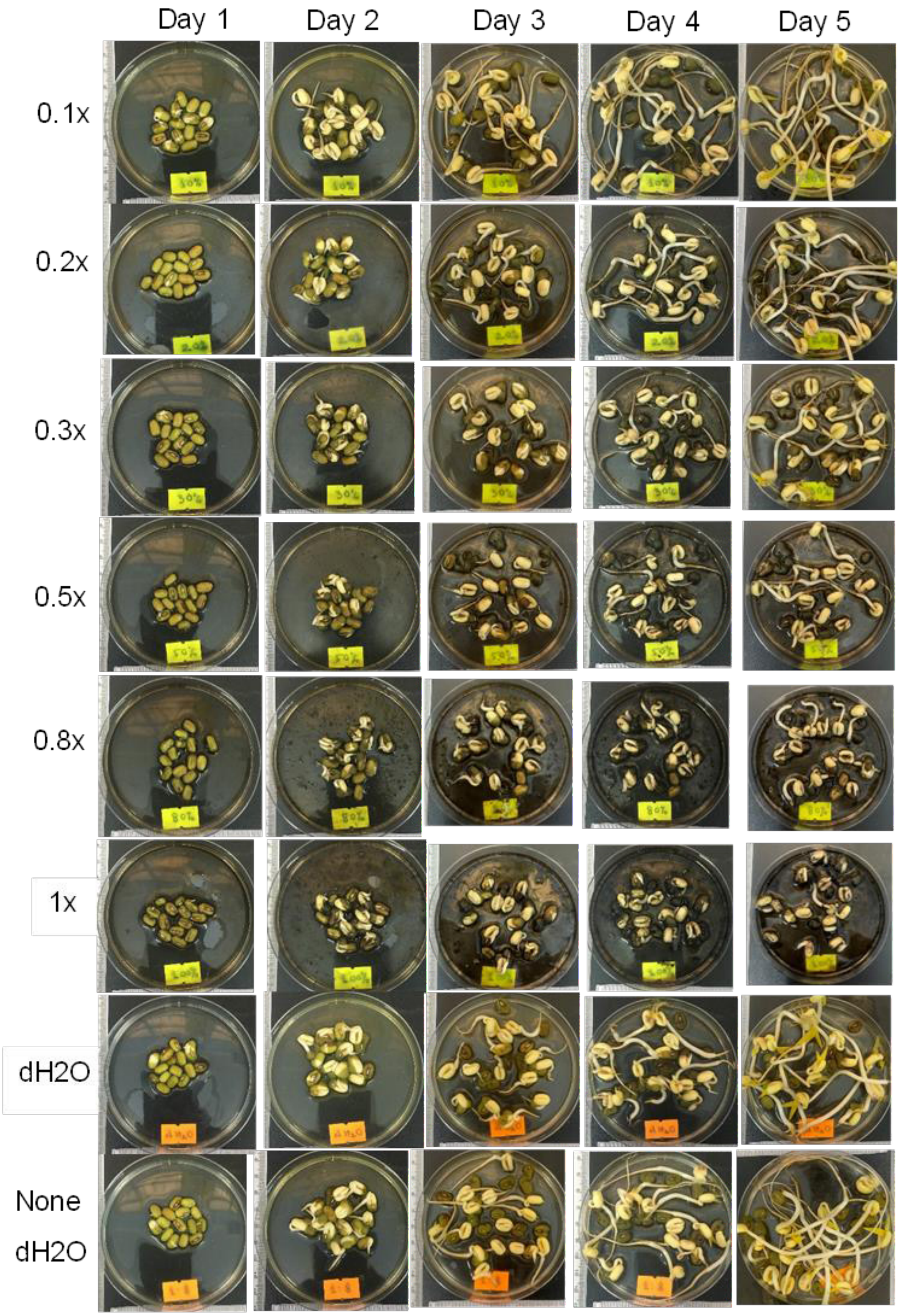

Figure 4. Photographs of mung bean growth in Petri plates over time

Figure 5. Photograph of bean sprouts grown in Petri plates over five days. The sprouts were treated with CDs at concentrations of 0.1×, 0.2×, 0.3×, 0.5×, 0.8×, and 1×, respectively (where 1× = 5.38 mg/ml)

It is important to note that the movement of mung beans over time in the Petri dish significantly influences the three-dimensional appearance of their growth. This variability contributes to a relatively large standard deviation when using ImageJ software. Furthermore, despite efforts to select visually similar mung beans, other factors may contribute to variations, such as genetic diversity among the beans, differences in seed age, and growth conditions (Vir, Lakhanpaul, Malik, Umdale, & Bhat, 2016). As depicted in Figure 5, the photograph of Petri dishes taken on the fifth day shows that the growth of mung bean plants is inconsistent. Despite being cultured under the same conditions, some seeds in each plate failed to germinate. Such variability is inevitable due to natural differences in the seeds. However, the most important observation is the consistent

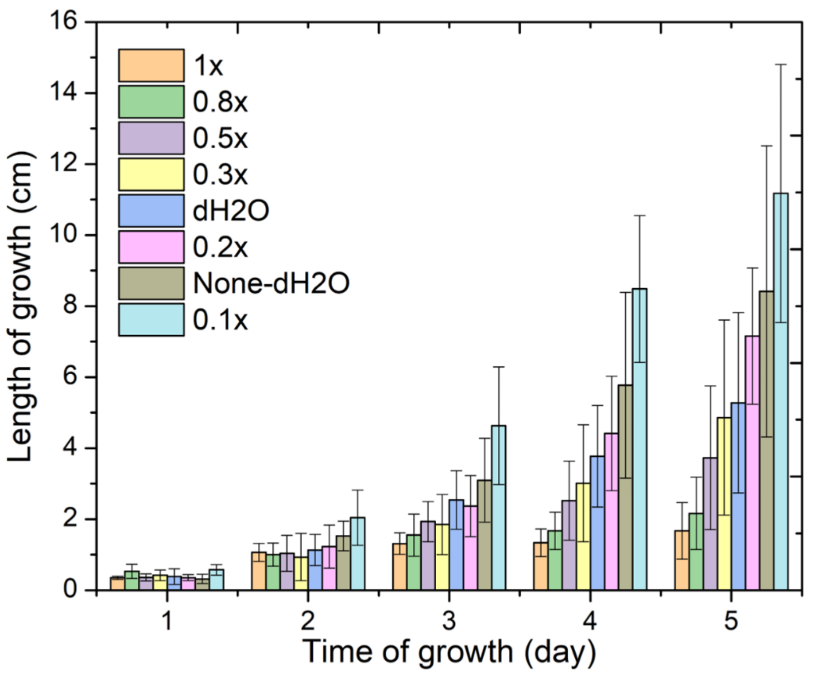

Figure 6. The toxicity of CDs was evaluated after 5 days of incubation of bean sprouts with different doses

trend in mung bean lengths across different concentrations of CDs, as shown in Figure 6. This suggests that random variability had a limited impact on the overall results.

2. Educational implementation

To assess the educational impact of the proposed experiment, a practical session was conducted with 25 undergraduate students, divided into five groups. The students performed the experimental steps to evaluate the impact of CDs on mung bean growth, as described in the Method section. Students actively participated in all steps, including synthesizing CDs using recycled batteries and observing mung bean growth over five days (Figure 7).

Figure 7. Photographs of several student activities during the experiment: a) conducting a survey, b) preparing for the electrochemical experiment, c) preparing mung beans, and d) watering the mung beans

The initial concentration of CDs produced by the students was 1X = 1.10 mg/ml, lower than the 1X = 5.38 mg/ml used in our main experiment. However, using this concentration and its dilutions (0.1×, 0.2×, 0.3×, 0.5×, and 0.8×), students gained an overview of the effects of CDs on mung bean growth and identified the optimal concentration for plant growth as 0.3X = 0.33 mg/ml (Figure 8).

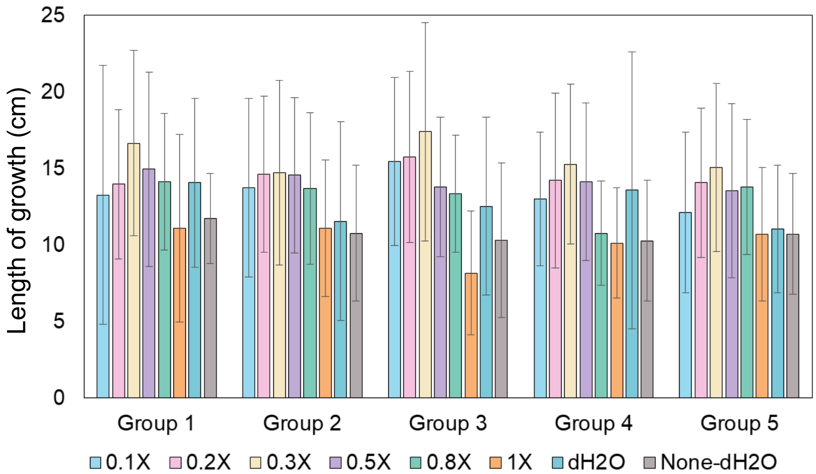

Figure 8. Length of mung bean sprouts grown in Petri plates over five days by five groups. The sprouts were treated with CDs at concentrations of 0.1×, 0.2×, 0.3×, 0.5×, 0.8×, and 1×, respectively (where 1× = 1.10 mg/ml)

Figure 9. Photograph of mung bean growth in Petri plates on the fifth day indicated that mung bean sprouts tend to grow vertically

photography was inaccurate. Instead, plant length was measured on the fifth day after removing the plants from the Petri dish and arranging them on a black background (Figure 10 to Figure 14). Additionally, since the experiment was conducted in a non-air-conditioned room during the summer in Hue City, the control sample (Non-dH2O group) showed lower plant growth compared to the distilled water sample (when compared with the data in Figure 6 of the main experiment). This was likely due to rapid evaporation in high temperatures, increasing the NaCl concentration in the saline solution sample, which negatively affected plant growth.

During the experiment, some groups forgot to turn off the ceiling lights after watering the plants, causing the mung bean sprouts to grow vertically toward the light (Figure 9) rather than spreading along the Petri dish. Consequently, measuring plant length over time using top-down

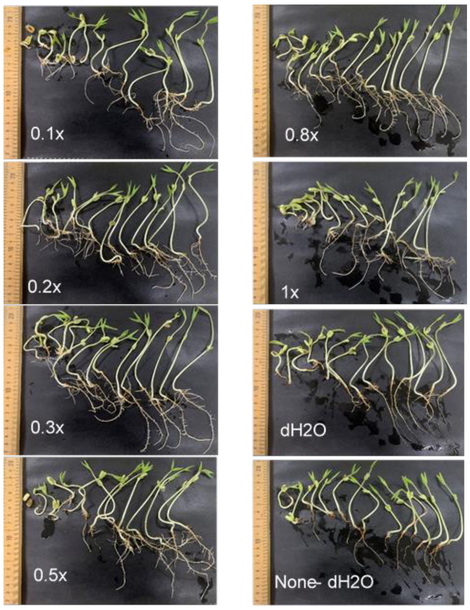

Figure 10. Bean sprouts grown in Petri plates for five days by Group 1. The sprouts were treated with CDs at concentrations of 0.1×, 0.2×, 0.3×, 0.5×, 0.8×, and 1×, respectively (where 1× = 1.10 mg/ml)

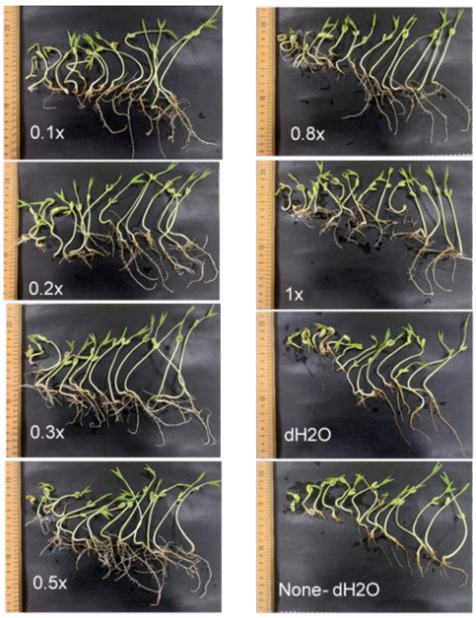

Figure 11. Bean sprouts grown in Petri plates for five days by Group 2. The sprouts were treated with CDs at concentrations of 0.1×, 0.2×, 0.3×, 0.5×, 0.8×, and 1×, respectively (where 1× = 1.10 mg/ml)

Figure 12. Bean sprouts grown in Petri plates for five days by Group 3. The sprouts were treated with CDs at concentrations of 0.1×, 0.2×, 0.3×, 0.5×, 0.8×, and 1×, respectively (where 1× = 1.10 mg/ml)

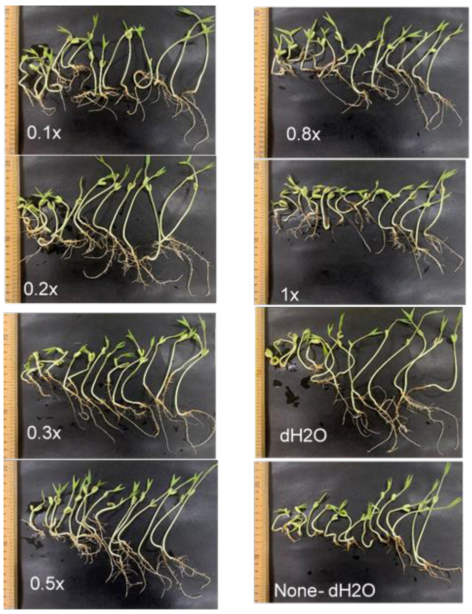

Figure 13. Bean sprouts grown in Petri plates for five days by Group 4. The sprouts were treated with CDs at concentrations of 0.1×, 0.2×, 0.3×, 0.5×, 0.8×, and 1×, respectively (where 1× = 1.10 mg/ml)

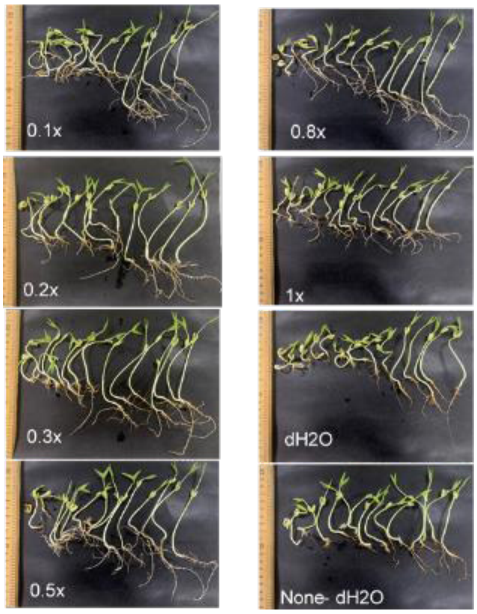

Figure 14. Bean sprouts grown in Petri plates for five days by Group 5. The sprouts were treated with CDs at concentrations of 0.1×, 0.2×, 0.3×, 0.5×, 0.8×, and 1×, respectively (where 1× = 1.10 mg/ml)

It is also important to consider the varying levels of experience and background knowledge among students when conducting these experiments. To ensure a better understanding, additional instructional support from the teacher can be beneficial. For undergraduate physics students, those who have taken courses related to materials science will likely find the experimental procedure straightforward, requiring minimal additional guidance. However, for high school students, a full class period may be necessary to provide them with a foundational understanding of nanoscale concepts before experimenting. This session would help them grasp fundamental physics concepts related to the nanoscale, providing essential context before engaging in the experiment.

3. Survey on educational evaluation

To assess students' perceptions and experiences, we administered three survey forms before the lecture, after the lecture, and after the experiment.

Survey 1: before the lecture

Topic: Understanding Carbon Dots and Nanophytotoxicity.

Instructions: This survey aims to assess your initial understanding of nanotechnology and the experiment with mung beans. Please answer honestly. Mark an (X) for the appropriate choice in multiple-choice questions. Your name is not required, and all information will remain confidential.

1. What does the prefix "nano-" mean?

   ____

2. How much do you know about the effects of substances (such as chemicals or nanoparticles) on plant growth?

   ( ) I know nothing
   ( ) I have a basic understanding
   ( ) I am familiar
   ( ) I know a lot

3. How much do you know about carbon dots (nano-sized carbon particles that glow)?

   ( ) I know nothing
   ( ) I have a basic understanding
   ( ) I am familiar
   ( ) I know a lot

4. How much do you know about recycling batteries or using old materials to make nanoparticles?

   ( ) I know nothing
   ( ) I have a basic understanding
   ( ) I am familiar
   ( ) I know a lot

5. How much do you know about measuring plant growth in scientific experiments?

   ( ) I know nothing
   ( ) I have a basic understanding
   ( ) I am familiar
   ( ) I know a lot

6. Do you think learning about nanotechnology is interesting? Why?

   ____

7. Have you heard about nanoparticles affecting plants? Do you think they are beneficial or harmful?

   ____

8. What do you hope to learn from the upcoming lecture and experiment?

   ____

Survey 2: after the lecture

Topic: Understanding Carbon Dots and Nanophytotoxicity.

Instructions: This survey aims to assess your understanding after the lecture on nanotechnology and the mung bean experiment. Please answer honestly. Mark an (X) for the appropriate choice in multiple-choice questions. Your name is not required, and all information will remain confidential.

1. What does the prefix “nano-” mean?

   ____

2. How much do you know about the effects of substances (such as chemicals or nanoparticles) on plant growth?

   ( ) I know nothing
   ( ) I have a basic understanding
   ( ) I am familiar
   ( ) I know a lot

3. How much do you know about carbon dots (nano-sized carbon particles that glow)?

   ( ) I know nothing
   ( ) I have a basic understanding
   ( ) I am familiar
   ( ) I know a lot

4. How much do you know about making carbon dots from recycled batteries using the electrochemical method?

   ( ) I know nothing
   ( ) I have a basic understanding
   ( ) I am familiar
   ( ) I know a lot

5. How confident do you feel about using ImageJ software to measure the length of mung bean plants?

   ( ) Not confident
   ( ) Slightly confident
   ( ) Confident
   ( ) Very confident

6. After the lecture, do you feel more interested in nanotechnology? Why?

   ____

7. How do you predict carbon dots will affect the growth of mung beans? Why?

   ____

8. Did the lecture meet your expectations? Would you like to personally conduct experiments on the effects of carbon dots on mung bean growth?

___

Survey 3: after the experiment

Topic: Understanding Carbon Dots and Nanophytotoxicity.

Instructions: This survey aims to assess your understanding, skills, and experiences after completing the mung bean experiment with carbon dots. Please answer honestly. Mark an (X) for the appropriate choice in multiple-choice questions. Your name is not required, and all information will remain confidential.

1. What does the prefix "nano-" mean?

___

2. How much do you know about the effects of substances (such as carbon dots) on plant growth?

( ) I know nothing
( ) I have a basic understanding
( ) I am familiar
( ) I know a lot

3. How much do you know about carbon dots (nano-sized carbon particles that glow)?

( ) I know nothing
( ) I have a basic understanding
( ) I am familiar
( ) I know a lot

4. Did the experiment help improve your ability to work in a team or communicate with classmates?

( ) Did not help
( ) Helped a little
( ) Helped a lot
( ) Helped very much

5. How confident do you feel about analyzing data (e.g., calculating the average length of plants)?

( ) Not confident
( ) Slightly confident
( ) Confident
( ) Very confident

6. What is the most important thing you learned from this experiment?

___

7. Was there anything surprising about the experiment? (E.g., the growth of mung beans or the effects of carbon dots)

___

8. How can you use the skills or knowledge from this experiment in your future studies or work?

___

4. Results of educational assessment

After collecting three survey forms administered before the lecture, after the lecture, and after the experiment, we compiled the students' responses as presented below. For multiple-choice questions, we organized the responses into tables. For open-ended questions, after reviewing the students' answers, we categorized and grouped them into main perspectives, with the number in parentheses indicating the number of students sharing similar views. The compiled survey responses were translated from Vietnamese to English. Details of the educational assessment results are listed in Tables 1 to 3.

Table 1. Results of survey 1: before lecture

1. What does the prefix "nano-" mean?				
Refers to particles with very small sizes (25)				
	I know nothing/ Not confident	I have a basic understanding/ Slightly confident	I am familiar/ Confident	I know a lot/ Very confident
2. How much do you know about the effects of substances (such as chemicals or nanoparticles) on plant growth?	1	22	2	
3. How much do you know about carbon dots (nano-sized carbon particles that glow)?		23	2	
4. How much do you know about making carbon dots from recycled batteries using the electrochemical method?		21	3	1
5. How confident do you feel about using ImageJ software to measure the length of mung bean plants?	7	10	6	2
6. After the lecture, do you feel more interested in nanotechnology? Why?				
- More interested because the lecture introduced new technology and its impacts on daily life, with potential practical applications (5) - More interested because the lecture provided new knowledge and guided hands-on experimental activities (8) - More interested because the lecture content was engaging and accessible (7) - More interested because of a desire to conduct experiments to investigate its effects on mung bean growth (5)				
7. How do you predict carbon dots will affect the growth of mung beans? Why?				
- Carbon dots will positively affect mung bean growth (11) - Carbon dots will affect mung bean growth depending on the concentration of the applied solution (8) - Carbon dots will negatively affect mung bean growth (6)				
8. Did the lecture meet your expectations? Would you like to personally conduct experiments on the effects of carbon dots on mung bean growth?				
- The lecture met my expectations, and I want to personally conduct experiments to observe the effects of carbon dots on mung bean growth (22) - The lecture met my expectations by providing new knowledge about nanotechnology (2) - The lecture had an engaging atmosphere and fostered good collaboration (1)				

Table 2. Result of survey 2: after lecture

<table>
<tr><td colspan="5">1. What does the prefix “nano-” mean?</td></tr>
<tr><td colspan="5">Refers to particles with very small sizes (25)</td></tr>
<tr><td></td><td>I know nothing/ not confident</td><td>I have a basic understanding/ slightly confident</td><td>I am familiar/ confident</td><td>I know a lot/ very confident</td></tr>
<tr><td>2. How much do you know about the effects of substances (such as chemicals or nanoparticles) on plant growth?</td><td>1</td><td>22</td><td>2</td><td></td></tr>
<tr><td>3. How much do you know about carbon dots (nano-sized carbon particles that glow)?</td><td></td><td>23</td><td>2</td><td></td></tr>
<tr><td>4. How much do you know about making carbon dots from recycled batteries using the electrochemical method?</td><td></td><td>21</td><td>3</td><td>1</td></tr>
<tr><td>5. How confident do you feel about using ImageJ software to measure the length of mung bean plants?</td><td>7</td><td>10</td><td>6</td><td>2</td></tr>
<tr><td colspan="5">6. After the lecture, do you feel more interested in nanotechnology? Why?</td></tr>
<tr><td colspan="5">- More interested because the lecture introduced new technology and its impacts on daily life, with potential practical applications (5)
- More interested because the lecture provided new knowledge and guided hands-on experimental activities (8)
- More interested because the lecture content was engaging and accessible (7)
- More interested because of a desire to conduct experiments to investigate its effects on mung bean growth (5)</td></tr>
<tr><td colspan="5">7. How do you predict carbon dots will affect the growth of mung beans? Why?</td></tr>
<tr><td colspan="5">- Carbon dots will positively affect mung bean growth (11)
- Carbon dots will affect mung bean growth depending on the concentration of the applied solution (8)
- Carbon dots will negatively affect mung bean growth (6)</td></tr>
<tr><td colspan="5">8. Did the lecture meet your expectations? Would you like to personally conduct experiments on the effects of carbon dots on mung bean growth?</td></tr>
<tr><td colspan="5">- The lecture met my expectations, and I want to personally conduct experiments to observe the effects of carbon dots on mung bean growth (22)
- The lecture met my expectations by providing new knowledge about nanotechnology (2)
- The lecture had an engaging atmosphere and fostered good collaboration (1)</td></tr>
</table>

Table 3. Result of survey 3: after experiment

<table>
<tr><td colspan="5">1. What does the prefix “nano-” mean?</td></tr>
<tr><td colspan="5">Refers to particles with a size on the order of 10^{-9} meters (4)
Refers to particles with very small sizes (21)</td></tr>
<tr><td></td><td>I know nothing/ did not help/ not confident</td><td>I have a basic understanding/ helped a little/ slightly confident</td><td>I am familiar/ helped a lot/ confident</td><td>I know a lot/ helped very much/very confident</td></tr>
<tr><td>2. How much do you know about the effects of substances (such as carbon dots) on plant growth?</td><td></td><td>18</td><td>5</td><td>2</td></tr>
<tr><td>3. How much do you know about carbon dots (nano-sized carbon particles that glow)?</td><td></td><td>17</td><td>5</td><td>3</td></tr>
<tr><td>4. Did the experiment help improve your ability to work in a team or communicate with classmates?</td><td></td><td>4</td><td>12</td><td>6</td></tr>
<tr><td>5. How confident do you feel about analyzing data (e.g., calculating the average length of plants)?</td><td></td><td>10</td><td>10</td><td>5</td></tr>
<tr><td colspan="5">6. What is the most important thing you learned from this experiment?</td></tr>
<tr><td colspan="5">- Understood the effects of carbon dots on plant growth (17)
- Learned that achieving good experimental results requires careful selection of experimental samples from the start (1)
- Learned how mung beans germinate and their growth process (2)
- Learned how to use software to measure mung bean length after conducting the experiment (4)
- Learned that a 30% concentration of carbon nanoparticles promotes the best plant growth (1)</td></tr>
<tr><td colspan="5">7. Was there anything surprising about the experiment? (E.g., the growth of mung beans or the effects of carbon dots)</td></tr>
<tr><td colspan="5">- The growth of mung beans was contrary to my initial predictions (7)
- The overall growth of mung beans depended on the concentration of the solution, with higher concentrations leading to weaker growth (9)
- Even under the same conditions, the growth of mung beans showed differences (1)
- The growth of mung beans was as I had predicted from the start (3)
- The growth of mung beans occurred quite rapidly (2)
- Other factors such as the initial sample, air, environment, and watering method also affected mung bean growth (3)</td></tr>
<tr><td colspan="5">8. How can you use the skills or knowledge from this experiment in your future studies or work?</td></tr>
<tr><td colspan="5">- Can enhance knowledge and understanding (1)
- Developed teamwork and responsibility skills (2)
- Currently unsure about specific applications (2)
- Can apply software skills in research (2)
- Can apply nanotechnology in agriculture and daily life (4)
- Indicated "Yes" but did not specify details (5)
- Can apply in learning through hands-on experiences and experiments (9)</td></tr>
</table>

CONCLUSION

This study employs carbon dots (CDs), synthesized electrochemically from recycled battery graphite, to explore nanomaterial toxicity through a practical mung bean experiment. The results revealed a significant difference in growth and development between control samples and mung bean sprouts treated with CD solutions. Beyond its research value, this experiment incorporates physics concepts, such as electrochemical synthesis and excitation-dependent photoluminescence, to create an accessible and interdisciplinary STEM activity. Following classroom implementation, the activity proved to be an effective educational tool. It engaged students in hands-on learning, encouraged them to explore both the benefits and risks of nanotechnology, and raised environmental awareness. The experiment aligns with the Vietnamese Grade 10 Specialized Physics Study Module and can be effectively implemented as a classroom project to investigate nanomaterial properties. Additionally, it is adaptable for undergraduate laboratory courses in nanoscience and nanotechnology.

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