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Academic Empowerment of Gifted Students: Investigating the Allelopathic Effect of *Eucalyptus globulus* Labill Extract in Different Cultures with the Addition of Hydrogel as a Water Source

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Student empowerment emphasizes enabling students to become protagonists in their learning process, fostering intellectual autonomy and growth. This approach is particularly crucial for gifted students to prevent academic disengagement. This study aimed to support the academic and scientific development of gifted students by investigating the allelopathic effects of an *Eucalyptus globulus* Labill aqueous extract on common-bean and radish crops, using a hydrogel as the primary water source. The germination assay was conducted in Petri dishes and evaluated across four different treatments over a period of seven days. The results demonstrated that the hydrogel combined with eucalyptus extract (1:13, gelatin:extract (w/w)) exerted an inhibitory effect on both crops, particularly on radish germination. Furthermore, analysis of key physiological indices revealed that the hydrogel treatment promoted rapid germination but resulted in an unbalanced initial growth pattern (low Dickson Quality Index; high Robustness Index). This research contributes to innovative pedagogical practices by demonstrating how authentic scientific inquiry empowers gifted students, fostering critical thinking and engagement in interdisciplinary areas. The findings highlight the potential of combining allelopathic compounds and hydrogels to promote sustainable agricultural practices, allowing students to actively explore innovative solutions focused on the dual functions of these components in crop management and water conservation.

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1. Introduction

Student empowerment is an educational approach that establishes students as active agents in learning, fostering autonomy, creativity, and responsibility [1, 2]. This perspective is essential for addressing the needs of gifted students—individuals with above-average potential in domains such as intelligence or specific talent—who require stimulating experiences to fully develop their potential, thereby preventing stagnation and low engagement. In this sense, schools must act as inclusive spaces, where taking the lead in learning develops essential critical skills, such as innovation and problem-solving [3, 4]. The identification of these students follows Brazilian national criteria, defined by the National Education Guidelines and Framework Law (Law No. 9,394/1996) and the CNE/CEB Resolution No. 4/2009 [5, 6]. These guidelines, widely used in state schools, direct the evaluation of exceptional academic performance, creativity, and potential for development across different areas of knowledge [6, 7].

In this context, offering an education that values and encourages student leadership becomes especially relevant for students with high abilities. Educational attention to gifted students therefore represents a strategic investment in the development of society's human potential. The growing global interest in this area reflects the search to maximize the capabilities of these students for the benefit of the community [8].

To this end, it is essential that schools provide enriching experiences that align with the abilities and interests of gifted students, promoting the full development of their talents and preventing the disuse of their exceptional abilities [2]. Incorporating scientific research into educational practices is an effective way to promote student empowerment, particularly for gifted learners [9]. By engaging students in hands-on, inquiry-based projects, they not only acquire technical knowledge but also develop essential skills such as problem-solving, critical thinking, and innovation. This study exemplifies such an approach by integrating chemistry and biology to investigate the allelopathic effects of *Eucalyptus globulus* Labill extracts on crops.

Allelopathy is a biological phenomenon in which plants release chemical compounds, known as allelochemicals, into the environment for communication. It is known that low productivity is directly related to this effect and is mediated mainly by biomolecules called allelochemicals [10, 11].

These compounds can influence the growth, germination, and development of surrounding plant species and also microorganisms. In agriculture, allelopathy plays a dual role: while it can negatively affect crop productivity by inhibiting growth, it also offers potential solutions for managing invasive weeds and pests [12].

The selective nature of allelochemicals, which can either stimulate or inhibit germination depending on the concentration and species, makes them promising alternatives to conventional agrochemicals, aligning with the principles of sustainable agriculture [12].

The interaction of allelochemicals with environmental factors, such as water availability, further complicates their impact. Water is a critical resource in agriculture, and its efficient management is essential for ensuring crop productivity and sustainability [13].

Hydrogels, as superabsorbent polymers, present an innovative solution to this challenge. These materials can retain and gradually release water, enhancing root development and reducing irrigation needs. Hydrogel also creates a microenvironment that supports the gradual delivery of nutrients or bioactive compounds, such as allelochemicals, directly to the plant roots [14].

The synergy between allelopathy and hydrogel technology opens new avenues for optimizing agricultural practices. By incorporating allelopathic compounds into hydrogels, it is possible to control the release of these compounds, maximizing their positive effects on crop management while minimizing potential negative impacts. For instance, the controlled delivery of *Eucalyptus globulus* extracts through hydrogel formulations can help suppress the growth of invasive weeds like radish (*Raphanus sativus* L.), which compete with desirable crops such as common-beans (*Phaseolus vulgaris* L.). This approach not only improves crop yields but also reduces the reliance on chemical herbicides, contributing to more sustainable agricultural practices [10].

These allelopathic compounds can be incorporated into the hydrogel, which are superabsorbent polymers, which in the presence of water increase their mass by up to 400 times and can be used directly in the soil, both in their dry form and in their hydrated form [14].

Eucalyptus species, particularly *Eucalyptus globulus*, are widely cultivated in tropical and subtropical regions of Brazil, where they are recognized for their high productivity and adaptability. The allelopathic effects of eucalyptus have been extensively studied, revealing their potential to inhibit the growth of certain plant species. However, the practical application of these findings in agriculture remains underexplored. By combining the allelopathic properties of eucalyptus with the water-retention capabilities of hydrogels, this study seeks to develop innovative strategies for crop and weed management [15, 16].

In addition to addressing these scientific and practical challenges, this project aims to empower gifted students by involving them in all stages of the research process. From designing experiments to analyzing results, students take on a central role, developing their scientific skills and contributing to the advancement of sustainable agriculture. This experience not only enhances their academic and professional prospects but also fosters a lifelong interest in science and innovation [16, 17].

The present study investigated the allelopathic effects of aqueous extracts of *Eucalyptus globulus* Labill leaves, focusing on their chemical properties and interactions with plant growth processes. To enhance the practical application and interdisciplinary understanding, these allelopathic compounds were incorporated into a biodegradable hydrogel formulation and used as the primary water source. The experimental design included an analysis of the effects of these formulations on the germination and development of two distinct crops: common-beans (*Phaseolus vulgaris*) as a cultivated plant and radish (*Raphanus sativus* L.) as a potential weed. This integration of chemistry and biology is aimed not only at advancing sustainable agricultural practices but also at promoting deeper engagement and critical thinking among students. By emphasizing the role of allelochemicals, polymer science, and water management in agriculture, the project highlighted how fundamental chemistry concepts can lead to innovative and sustainable solutions.

Therefore, the objective of this work was to empower gifted students by engaging them in a hands-on scientific research project that integrates core concepts from chemistry and biology, while fostering their ability to apply this knowledge in real-world contexts.

2. Material and Methods

This study involved two students identified as gifted, both of whom were attended in the Gifted/High Abilities Room, Wolff Klabin State School – Elementary Secondary, Normal and Professional Education, Telêmaco Borba, PR, Brazil, in the afternoon. The participants are enrolled in the eighth grade of elementary school and attend regular classes at different schools in the morning: one of them studies at President Vargas Civic-Military State College, Telêmaco Borba, PR, Brazil, while the other remains at Wolff Klabin State School.

The identification of gifted students was conducted by specialized professionals and adhered to the Brazilian national criteria established by the National Education Guidelines and Framework Law (Law No. 9,394/1996) [5] and the Operational Guidelines for Specialized Educational Services in Basic Education (CNE/CEB Resolution No. 4/2009) [6]. This process involved assessments of the students' academic performance, cognitive profile, and intellectual potential—including creativity and problem-solving skills—to ensure the selected group was homogeneous in terms of abilities and educational needs [6,7]. Furthermore, we aimed to respect the school context and the individual challenges faced by each student, promoting an enriching experience that integrated scientific theory and practice.

The methodology adopted enabled gifted students to actively participate in all stages of scientific research [7]. The students investigated the allelopathic effects of *Eucalyptus globulus* Labill extract on different crops, integrating the use of hydrogel as a primary water source. They contributed to the design of the experiments, the conduct of germination tests, the analysis of data and the interpretation of results.

2.1 Experimental Study

The experimental study was conducted in the Chemistry Laboratory of President Vargas Civic-Military State College, Telêmaco Borba, PR, Brazil.

The methodology was developed based on Renzulli's Three Rings Theory [18], which proposes that above-average abilities, creativity and commitment to tasks are essential for the development of the potential of gifted students, in addition to principles of theory of active learning, as defended by [19].

The students were protagonists in all stages of the experiment, being guided and accompanied by the teacher at key moments to ensure scientific accuracy. The students investigated the environmental issues related to the disposal of eucalyptus leaves, considering that the Telêmaco Borba city is the capital of paper and cellulose [19], in addition to investigating the potential use of this waste for application in allelopathic studies. They participated in theoretical discussions on the importance of using biodegradable hydrogels in mitigating environmental impacts and in sustainable water management.

2.2 Identification and Collection of Plant Material

The species *Eucalyptus globulus* Labill, commonly cultivated in the region, was identified as a source of leaves considered agricultural waste. Approximately 1 kg of dry leaves, sourced from trees approximately 15 years old, was donated by local sources for subsequent extraction procedures.

2.3 Preparation of Eucalyptus Aqueous Extract

The students were responsible for carrying out all the preparation for the experiment, following previously discussed protocols, and conducting bioassays in the laboratory, including assembling Petri dishes, distributing seeds, and applying treatments.

The aqueous extract was prepared following the methodology proposed by [20], with modifications [18]. The collected dry leaves were ground using a mortar and pestle to achieve a particle size suitable for extraction. The concentration was standardized at 1 $g.10mL^{-1}$ (w/v), and the extract was utilized in its pure form. Tap water was used as the control treatment. For germination assays, Petri dishes were sanitized with 70% ethanol (v/v) and lined with qualitative filter paper. The treatments are described in Table 1.

Table 1. Treatments applied.

Control treatment*	Treatment 2*	Treatment 3	Treatment 4
3 $mL.day^{-1}$ of tap water	3 $mL.day^{-1}$ of the aqueous eucalyptus extract	Hydrogel formulated with tap water	Hydrogel formulated with aqueous eucalyptus

**Qualitative Filter paper used as support.* All treatments were monitored for 7 days.

Nine seeds of *Phaseolus vulgaris* L. (common-beans) or *Raphanus sativus* L. (radish) were uniformly distributed in each Petri dish. Germination was defined as the emergence of a radicle with a length of at least 2 mm.

2.4 Hydrogel Formulation

Under supervision, the students adopted the methodology by [14] to produce hydrogels, replacing k-carrageenan with colorless gelatin, due to the lower cost and greater accessibility of this material. The concentration of the extract in the hydrogel was 1:13, gelatin:extract (w/w), the hydrogel formulated with water followed the same proportion 1:13, gelatin:water (w/w). All steps of the process were rigorously recorded in a laboratory diary, ensuring the reproducibility and systematization of the procedures. The diagram of preparation by gifted students of eucalyptus extract, hydrogel, application of treatments, results and data analysis is shown in Figure 1.

2.5 Data Analysis

Students calculated germination percentage, Pearson correlation equation, Dickson quality index, germination efficiency and robustness index. They learned to use appropriate equations and interpreted the results about the initial hypothesis.

The experiment lasted seven days, with daily observations at the same time to record the number of germinated seeds. Root lengths were measured at the end of the experiment using a millimeter ruler, and the arithmetic mean was calculated using Equation (1):

$$X = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (1)$$

Where:

X = mean root length (mm)

x_i = individual root length measurements (mm)

N = total number of seeds germinated.

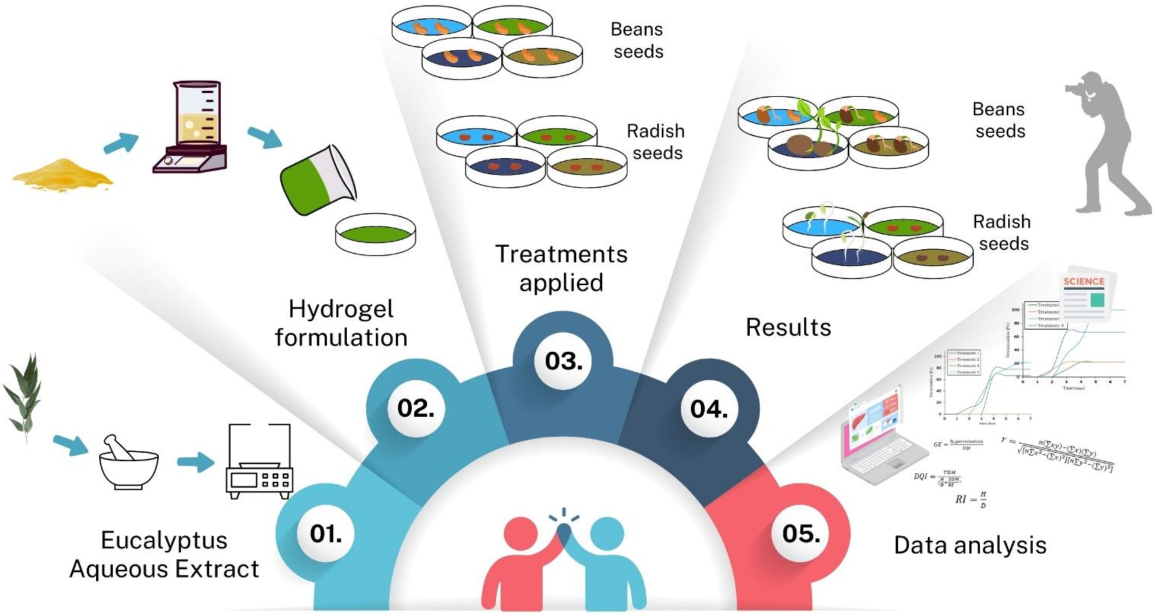

Fig. 1. Summary of experiments carried out by gifted students showing their empowerment.

2.6 Germination Percentage

The germination percentage (%) was calculated using a simple proportional rule, considering the total number of seeds (12) as equivalent to 100%.

2.7 Pearson's Correlation Coefficient (r)

The Pearson's correlation coefficient (r) is given by the following equation (Equation 2) [21]:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad (2)$$

Where:

r = Pearson correlation coefficient;

n = number of data points;

x and y = values of the two variables being correlated.

2.8 Dickson Quality Index (DQI)

The DQI was calculated using the values of TDM, H, D, SDM and RDM obtained at the end of the process, applying the following equation following the methodology proposed by [22]. The DQI was calculated using the Equation (3):

$$DQI = \frac{TDM}{\left(\frac{H}{D} + \frac{SDM}{RDM}\right)} \quad (3)$$

Where:

TDM = Total dry mass;

H = Plant height;

D = Diameter;

SDM = Shoot dry mass;

RDM = Root dry mass.

The evaluation of the DQI was conducted for each treatment (control, aqueous extract, hydrogel with water, and hydrogel with aqueous extract) with three replicates. This calculation was included to assess the overall morphological quality of the seedlings produced under each experimental condition.

2.9 Germination Efficiency (GE)

The Germination Efficiency (GE) was calculated using the values of total germinated seeds (%), and the DQI [22], applying the following formula as described by [23]. The GE was calculated using Equation (4):

$$GE = \frac{\%\ germination}{DQI} \quad (4)$$

2.10 Robustness Index (RI)

The RI was calculated based on the variability of the observed responses, the following formula as described by [24]. The RI was calculated using Equation (5):

$$RI = \frac{H}{D} \quad (5)$$

3. Results and Discussion

The results align with the objective of academically empowering gifted students by providing them with the opportunity to engage in scientific research, thereby fostering their critical thinking and innovation [25-28]. Active participation in this research allowed the students to practice analyzing and interpreting experimental data [28], deepening their understanding of allelopathy and the role of hydrogels in enhancing crop sustainability [14]. By applying these concepts and exploring sustainable agricultural tools, students were able to connect theoretical knowledge from chemistry (such as the study of biomolecules and polymers) with biological phenomena (like allelopathy) while deepening their understanding of environmental impact and alternatives for improving agricultural practices. This experience, considered crucial for developing advanced cognitive skills [25-28], confirms the importance of integrating experimental research into the curriculum for gifted students, as it is a powerful approach to connect theory and practice, stimulate curiosity, and deepen fundamental chemical concepts [29, 30].

3.1 Phaseolus vulgaris L. (common-beans)

The allelopathic effect of the aqueous extract of Eucalyptus leaves was investigated against common-beans and radish crops, which are considered weeds during certain times of the year. For this investigation, seed germination was evaluated according to the four treatments already shown in Table 1.

Through the experiments, the students observed that in both control treatment (watering the seeds only with water) and treatment 2 (watering the seeds with aqueous extract of *Eucalyptus globulus*), only two seeds germinated (Figure 2 (A and B)).

Fig. 2. (A) Common-beans seeds (control treatment – only water); (B) Common-beans with Eucalyptus extract only (treatment 2).

Seed germination is a complex process dependent on the optimal interaction between internal factors (of the seed) and external factors (of the environment).

An external factor that could harm seed germination is the fact that they remained submerged for a certain time when 3 mL of water or extract are added. This can cause what is known as hypoxia, a condition in which the seed is subjected to low levels of available oxygen during the germination process, which can therefore affect its germination. This effect has also been observed in studies with common-bean seeds (*Phaseolus vulgaris* L.), showing that longer periods during soaking can prevent germination [31].

However, since some seeds germinated, it can be inferred that the greatest contribution to low germination rate is related to internal factors. Seed quality is crucial for satisfactory germination. Seed vigor, as well as dormancy and mechanical damage, can directly impact germination. Seed vigor is defined as the capacity to emerge and establish seedlings rapidly across a wide range of environments. Dormancy prevents germination even under favorable environmental conditions, and seeds may have also suffered damage during harvesting, processing, or storage, making them more vulnerable to pathogens. Thus, while environmental limitations such as substrate absence and transient hypoxia contributed to the failure, the overall poor outcome suggests that inherent low vigor or a high incidence of damaged seeds in the initial lot likely exacerbated these environmental stresses, ultimately leading to the observed low germination percentage.

To evaluate the allelopathic effect of eucalyptus extract, the students used treatments 3 and 4 (Figure 4 (A and B), respectively).

In Figure 3, it is evident that using hydrogel as a water source (treatment 3), there was 100% germination of the seeds by the fifth day of the experiment, as shown in Figure 4. This demonstrates the potential of hydrogels in providing an optimal environment for seed germination by ensuring a consistent and gradual water release, which supports metabolic activation and radicle emergence.

Fig. 3. (A) Common-beans seeds with water-based hydrogel (treatment 3); (B) Common-beans seeds with hydrogel based on Eucalyptus extract (treatment 4).

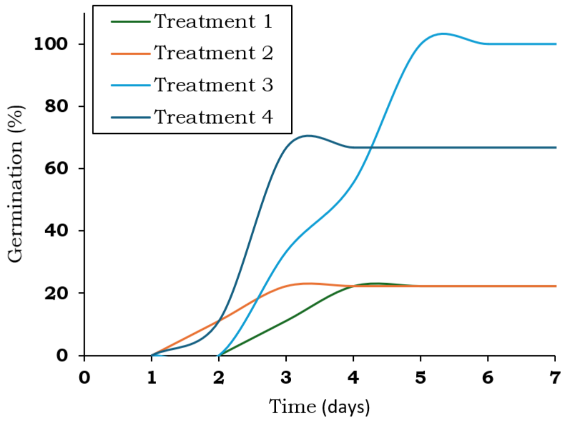

Fig. 4. Percentage of common-beans germination.

The use of hydrogels addresses a critical challenge in agriculture: water availability. Superabsorbent hydrogels have proven to be effective in retaining and releasing water gradually, optimizing both water use efficiency and crop productivity [32].

Hydrogels have been gaining increasing prominence as allies in agriculture. These superabsorbent structures have the capacity to retain large volumes of water in their polymeric networks, being able to absorb up to approximately 300% of their volume,11 gradually releasing it as plants need it. This mechanism not only improves water use efficiency but also promotes greater crop resilience under water stress conditions. This aligns with findings from [33], which highlight the effectiveness of hydrogels in enhancing moisture availability and promoting plant resilience in water-stressed conditions.

A comparative analysis of the germination treatments reveals that Treatment 4 (hydrogel formulated with eucalyptus extract) demonstrated a faster onset of germination than Treatment 3 (hydrogel with water). However, despite this promising start, Treatment 4 reached a maximum germination plateau near 70%, which is significantly lower than the 100% plateau achieved by Treatment 3 (hydrogel alone) (Figure 4). The observed difference suggests that, although the hydrogel improved the initial germination conditions, the inclusion of the eucalyptus extract resulted in a subsequent inhibition that limited the final germination rate and root development.

This outcome suggests the presence of allelopathic effects from the eucalyptus extract. Eucalyptus species are known for producing secondary metabolites (allelochemicals), which can inhibit the germination and growth of neighboring plants. These compounds, mainly phenolics and terpenoids [34], likely interfered with the metabolic pathways essential for germination or created an unfavorable chemical environment around the seeds.

Riveiro et al. [34] identified four compounds with a high level of confidence, collectively representing approximately 40% of the total content in the analyzed eucalyptus extracts: gallic acid, epicatechin, ferulic acid, and ellagic acid. Notably, gallic acid and ellagic acid were the two main compounds. These results were similar in other studies [35-37].

Such allelopathic behavior has been well-documented in studies such as [34,38,39], which highlight the potential phytotoxic effects of eucalyptus extracts on seed germination. Importantly, despite the reduced growth, the seeds treated with the eucalyptus-based hydrogel still germinated, achieving the primary objective of demonstrating viability under the influence of the extract. This partial inhibition suggests a controlled and selective growth suppression, which could be strategically advantageous. For instance, the application of eucalyptus-based hydrogels could serve as an innovative approach to manage weed growth, targeting undesired plants while conserving water and resources.

These findings reinforce the dual potential of hydrogels: as moisture-retaining agents and as carriers for bioactive compounds with specific agricultural applications. This approach could pave the way for sustainable weed management practices that reduce reliance on synthetic herbicides while enhancing water use efficiency [40].

3.2 *Raphanus sativus L. (*radish*)*

The allelopathic effect of eucalyptus extract was also investigated in the crop Raphanus sativus L. (radish). This species was selected for its easy access and widespread use. Furthermore, its rapid propagation and invasive nature at certain times of the year mean that radish can be classified as a weed in certain agricultural contexts [41].

For this investigation, seed germination too was evaluated according to Table 1. Through the experiments, the students observed that unlike common-bean seeds, the radish seeds germinated in the control treatment (watering the seeds only with water), and there was no germination in treatment 2 (watering the seeds with aqueous extract of *Eucalyptus globulus*) (Figure 5 (A and B)).

Analyzing the results obtained in the radish study, it is observed that the germination rate in the control treatment was high compared to common bean, which suggests the absence of the internal and external factors previously mentioned (e.g., low seed vigor or insufficient environment). Conversely, no seed germination occurred in Treatment 2 (aqueous eucalyptus extract). This fact strongly suggests that the eucalyptus extract exerted a direct, highly inhibitory allelopathic effect on the radish seeds.

These findings highlight physiological differences between the species, indicating that the growth inhibition resulting from exposure to the plant extract varies significantly depending on the target species studied.

Therefore, to prove the allelopathic effect of eucalyptus extract, the students used treatments 3 and 4 (Figure 6 (A and B)).

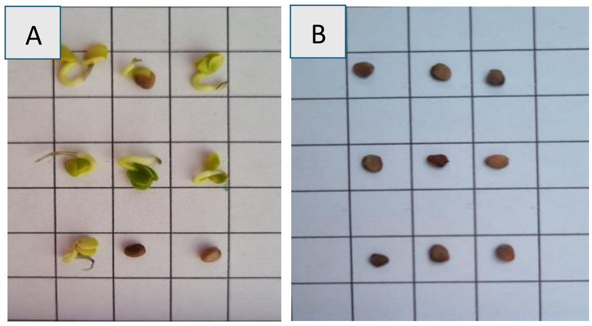

Fig. 5. (A) Radish seeds (control treatment); (B) Radish with Eucalyptus extract only (treatment 2).

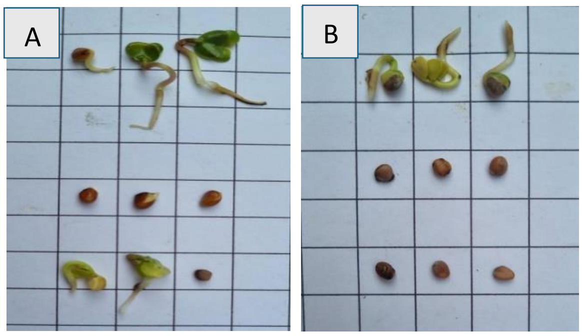

Fig. 6. (A) Radish seeds with water-based hydrogel (treatment 3); (B) Radish seeds with hydrogel based on Eucalyptus extract (treatment 4).

In Figure 6, it is observed that using hydrogel as a water source in treatment 3 promoted greater seed germination, highlighting its beneficial effect by providing not only a continuous water supply but also a favorable environment for the initial development of seedlings. In contrast, in treatment 4, where hydrogel was combined with eucalyptus extract, germination was reduced, suggesting an allelopathic effect of the extract, which may have inhibited the development of radish seeds. These results emphasize the importance of hydrogel as a beneficial resource for germination, if it is not associated with compounds with inhibitory potential.

The use of hydrogel in combination with eucalyptus extract may have interesting applications in agriculture. While hydrogel alone serves as an efficient source of water and nutrients for plants, its association with eucalyptus extract can enhance allelopathic effects, hindering the germination and development of certain species [42]. In the case of radish, the results indicate that this combination inhibited its growth, suggesting a potential use of this approach for managing unwanted plants (Figure 7).

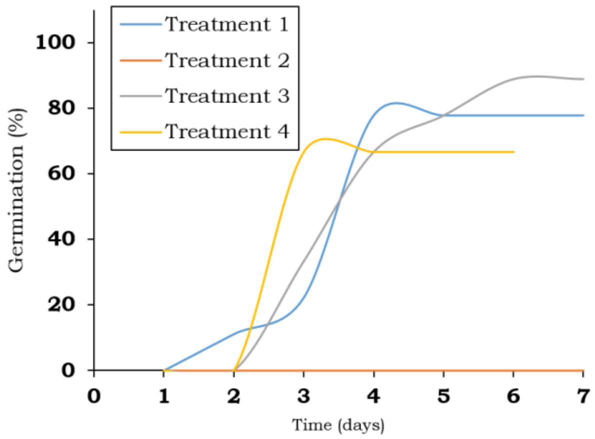

Fig. 7. Percentage of radish germination.

At certain times of the year, radish can be considered a weed, as it competes with economically important crops such as soybeans, which are often planted after its weed emergence in agricultural fields. Thus, applying hydrogel with eucalyptus extract could represent a natural alternative for the selective control of radish, reducing the need for synthetic herbicides [43]. However, further studies are needed to assess the feasibility of this strategy on a larger scale and its impact on other crops and soil health.

3.3 Impact of Hydrogel on Initial Common-Bean Growth

Students calculated germination percentage, Pearson correlation equation, DQI, germination efficiency and robustness index for the common-bean crop, after using treatment 3 for seven days. These results provide a detailed view of common-bean growth under treatment 3 (Table 2).

Table 2. Growth performance of common-beans under hydrogel treatment.

TDM	H	D	SDM	RDM	DQI	GE	RI	r
0.16±0.03*	3.00±1.87*	0.15±0.04*	0.14±0.03*	0.02±0.02*	0.006±0.001*	17856,97±4164.88*	18.24±8.67*	0.97

**Mean ± standard deviation.* TDM: Total Dry Mass; H: Plant Height; D: Diameter; SDM: Shoot Dry Mass; RDM: Root Dry Mass; DQI: Dickson's Quality Index; GE: Germination Efficiency; RI: Robustness Index; r: Pearson's correlation coefficient.

Quality Index (DQI) [22] is an important metric for assessing seedling robustness, considering the relationship between height, diameter and biomass [44]. This calculation considers factors that indicate that the plant is growing in a balanced manner, since a very high value may suggest that the seedling is more susceptible to toppling over. It also considers the balance between the aerial part and the roots, since good root development is essential for the absorption of nutrients and water [45]. Current literature says that a higher value indicates better quality [46].

Therefore, the value obtained (0.006, Table 2) is relatively low, suggesting that the treatment may not have favored balanced structural development. However, the TDM was 0.16, mainly due to the short growth period (only 7 days). Therefore, DQI tends to increase as the plant develops more biomass. Therefore, these results suggest that if the experiment were conducted for a longer period, the TDM would increase and the DQI would probably improve.

Regarding GE, which is used to describe the development and performance of plants [47], for this experiment, a relatively high value was considered (17856.97), since GE is calculated by dividing the germination rate by the DQI, therefore, a low value in the denominator causes the result to be artificially high. Since the germination rate was high (100%), despite the GE value, this means that all the seeds studied germinated successfully. Suggesting that the environment provided by treatment 3 was favorable to germination, ensuring good humidity and adequate conditions for seed development.

Although the seeds germinated well, the low DQI also suggests that the seedlings were relatively fragile during the study period and did not develop a robust structure. This probably occurred because there was rapid but unbalanced initial growth, favoring height instead of diameter and root. And most importantly, the plants still did not have enough time to accumulate biomass and strengthen their structures.

The RI is an indicator of the structural balance of seedlings, measuring the proportion between height and stem diameter. A lower RI suggests more robust and balanced growth, while a very high RI may indicate that the plants grew with thinner and less resistant stems [24,48].

The RI (18.24) may mean that the plant's height is greater than its diameter. This type of growth can make seedlings more fragile and susceptible to toppling over. However, if the study had been carried out over a longer period, the plants could probably invest more in thickening their stems, since hydrogel provides balanced nutrients, reducing the RI. In addition, the seeds were monitored in a 9cm diameter Petri dish, and this may be due to competition for space, since greater spacing between plants can help prevent excessive growth in height [49].

To assess whether total biomass has an influence, that is, how the hydrogel can influence the distribution of biomass in the plant, and if there is a strong correlation, meaning that plants with more biomasses tend to have better structural quality (relationship between TDM and DQI), Pearson's correlation coefficient was used [21].

This value of 0.97 was very strong, and this suggests that the hydrogel favored the growth of biomass in a balanced way, resulting in more structured and better-quality plants [48].

4. Conclusions

This study successfully engaged gifted students in a scientific inquiry, achieving the objective of academic empowerment by integrating core concepts from chemistry and biology and fostering the application of theoretical knowledge in a real-world context. The hands-on project emphasized the development of key research skills, including hypothesis formulation, critical thinking, data analysis, and experimental design, providing students with a significant role in their learning and reinforcing their connection to contemporary sustainability challenges.

From a scientific perspective, the findings demonstrate the dual role of hydrogels and allelopathic compounds in early plant development. The application of biodegradable hydrogel enhanced seed germination and initial growth by providing a continuous and controlled water supply, as evidenced by the 100% germination rate achieved by common-bean seeds in Treatment 3. Conversely, the incorporation of the *Eucalyptus globulus* extract into the hydrogel (Treatment 4) resulted in an observable inhibitory effect on both common-bean and radish seeds, confirming the phytotoxic properties of the extract and suggesting its potential for selective weed management and reduced reliance on synthetic herbicides.

However, key physiological indices indicated that while the hydrogel promoted rapid germination, the seedlings exhibited an unbalanced initial growth pattern. The relatively low Dickson Quality Index (DQI) and the high Robustness Index suggested that seedlings favored height over structural robustness (high height-to-diameter ratio), making them potentially more susceptible to mechanical stress. This implies that while hydrogels effectively support germination, additional structural reinforcement may be necessary to enhance long-term seedling resilience, reinforcing the positive role of hydrogel in balanced growth when applied under optimal conditions.

In conclusion, the integration of hydrogels and allelopathic compounds serves as a promising avenue for improving agricultural sustainability while simultaneously functioning as an innovative and powerful educational platform for students engaged in interdisciplinary scientific research. Future studies should focus on exploring the long-term effects of hydrogel use on plant development, assessing its feasibility in large-scale agricultural applications, and investigating its impact on soil microbiota and nutrient availability.

Author Contributions

Sharise Beatriz Roberto Berton: Methodology; Resources; Writing - Original Draft; Validation; Supervision; Writing - Review & Editing. Jomar Berton Junior: Writing - Original Draft; Resources; Project Administration; Supervision; Writing - Review & Editing. Vinícius Miranda Lopes: Investigation; Resources; Formal analysis. Miguel Celestino: Investigation; Resources; Formal analysis. Milena do Prado Ferreira: Investigation; Resources; Formal analysis; Writing - Original Draft. Ana Lídia Moura Woruby: Visualization; Formal analysis; Writing - Original Draft. Nayara Amany Dobzinski: Visualization; Formal analysis; Writing - Original Draft. Vera Lúcia Galvão: Writing - Original Draft; Supervision; Writing - Review & Editing. William Renzo Cortez-Vega: Investigation; Writing - Original Draft; Resource; Writing - Review & Editing; Supervision.

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