education sciences

MDPI

Article

A Case Study of an Antibiotic Discovery Laboratory Autonomous Learning Assignment—An Evaluation of Undergraduate Students' Disciplinary Bias

Nadav Badrian [1], Lilach Iasur-Kruh [2], Yael Ungar [2] and Iris Sonia Weitz [2,*]

[1] English Studies Unit, Braude College of Engineering, Karmiel 2161002, Israel; nadavbdn@braude.ac.il
[2] Department of Biotechnology Engineering, Braude College of Engineering, Karmiel 2161002, Israel; iasur@braude.ac.il (L.I.-K.); yaelungar210@gmail.com (Y.U.)
* Correspondence: irisweitz@braude.ac.il

Abstract: Current higher education trends are moving towards interdisciplinary curricula to provide new tools for solving complex issues. However, course design and learning tracks still create divisions between scientific disciplines. This study aimed to evaluate the disciplinary bias of second-year undergraduate students of biotechnology engineering in the organic chemistry laboratory class through a laboratory setting involving blended disciplines. An experiment on antibiotic discovery that integrates parallel and combinatorial organic chemistry syntheses with microbiology techniques was chosen. As a part of an activity, students had free choice in designing the arrangement of the organic compounds and the two bacterial species by setting up the layout for a 96-well plate. The study visually analyzed students' plate layouts (n = 74) according to discipline classification and the spatial arrangements of organic compounds (e.g., products and libraries). The results identified four themes that are suggested to reflect students' vertical, lateral, and interdisciplinary thinking, as most were found to be in the procedural knowledge range and between Bloom's application and analysis dimensions. Using this study's thematic analysis methodology in chemistry and related educational fields can provide a pedagogical reflective tool and advance personalized teaching and interdisciplinarity.

Keywords: autonomous learning; hands-on learning; thematic analysis; interdisciplinary; laboratory instruction; STEM; higher education

check for updates

Citation: Badrian, N.; Iasur-Kruh, L.; Ungar, Y.; Weitz, I.S. A Case Study of an Antibiotic Discovery Laboratory Autonomous Learning Assignment—An Evaluation of Undergraduate Students' Disciplinary Bias. *Educ. Sci.* **2024**, *14*, 1176. https://doi.org/10.3390/educsci14111176

Academic Editor: Sang Yeoup Lee

Received: 3 August 2024
Revised: 11 October 2024
Accepted: 23 October 2024
Published: 28 October 2024

1. Introduction

Most current scientific research is concentrated on solving real-world problems. These types of problems are complex and approaching them requires interdisciplinary knowledge, critical thinking, data analysis, and diverse solutions [1]. Applying such skills in Science–Technology–Engineering–Mathematics (STEM) involves a shift from the traditional physics paradigm of science, focused on separating disciplines, to an engineering paradigm of science that dictates a change in engineering education and the training of future scientists [2]. The change is reflected in cross- and inter-disciplinary perspectives, teaching metacognitive skills, and producing metacognitive scaffolds (i.e., conceptual frameworks in the teaching process) [3]. This change in the teaching paradigm parallels with new educational concepts of autonomous, relevant, self-directed learning, focusing on the learners and their ability to self-direct and reflect [4].

Even though current biotechnology engineering programs are multidisciplinary, their learning programs and curricula are still fragmentized and divided with traditional paradigms at their base [3]. This translates to an artificial division as learners become acquainted with various disciplines separately and are required to make the interdisciplinary combinations only towards the end of their studies in their final projects and internships. It is assumed that improving metacognitive skills will provide a sound basis for undergraduate students' learning and professional future through the introduction of blended disciplinary learning activities. However, there are obstacles to overcoming this challenge in building such activities that produce interdisciplinary learning in practice [5,6]. While plenty of research can be found focusing on motivation [7], self-reported student engagement [8], the teaching array, and technical details in the pedagogical framework [9], there is a lack of emphasis on assessing the cognitive change toward interdisciplinarity. To this end, it is necessary to evaluate students' disciplinary cognitive and psychological biases [10] and analyze their thinking on more than one disciplinary scale from a macro perspective, not solely relying on self-report.

Laboratory class is considered an excellent platform for building interdisciplinary connections between new subjects and previous knowledge in chemistry, biology, and other majors, following relevant examples from actual research [11–15]. For example, the subject of antibiotics integrates organic synthesis with drug discovery strategies and microbiology science [16–18]. Moreover, the increase in incidents of resistance to antibiotics and the emerging number of infectious diseases highlights the need for continuous and ongoing efforts to discover new antimicrobial agents [19–21], and accordingly, to prepare students with the appropriate skills for work on interdisciplinary topics.

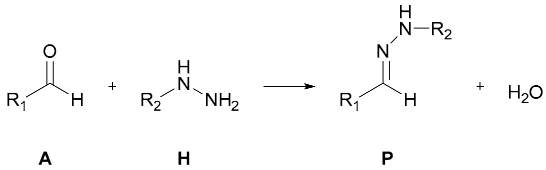
Hydrazone compounds are known for their antibiotic properties [22,23] and commonly are synthesized by a condensation reaction between aldehyde and hydrazine. The reaction goes to completion after a few minutes without using additional reagents. Usually, no further purification and isolation steps are required for the characterization of the antimicrobial activity. Therefore, the synthesis of hydrazones and screening of their antibiotic activity have been found to be suitable for teaching the concept of combinatorial chemistry and its application in antibiotic discovery [24] as published previously by S. E. Wolkenberg and A. I. Su [25] and in the article by C. J. Nichols and L. F. Hanne [26].

In the current study, the antibiotic discovery experiment utilized the experimental setup of a 96-well plate, widely used in both academia and industry on a daily basis. This elegant and efficient technique for examining the potential anti-bacterial activity of compounds is used instead of the agar plate (Petri dish) method. It allows the introduction of two experimental units described by different drug discovery methodologies, namely parallel versus combinatorial organic chemistry syntheses. In addition, the implantation of a 96-well plate enabled a visual interdisciplinary representation of both chemical and microbial designs as can be shown through the different geometric arrangements of the organic compounds and the types of bacteria. Investigating the plate layouts planned and created autonomously by students can be used as a new reflective tool for students' interdisciplinarity understanding skills.

This research is a case study correlating students' experimental design choices to elicit and analyze their disciplinary bias; the insights into their varying thinking schemes will be discussed.

2. The Antibiotic Discovery Experiment

In the experiment, students of the Organic Chemistry Lab course synthesized hydrazone derivatives (Scheme 1). The experimental procedure used three aldehydes (A1, A2, and A3) and three hydrazines (H1, H2, and H3) to prepare a matrix of hydrazone products (the compounds labeled P1–P9). The chemical structures are shown in Appendix A. The nine individual products are yielded by parallel synthesis as described in Table 1. These hydrazone syntheses can also be utilized for a combinatorial strategy, in which the libraries (mixtures of compounds) are obtained by appropriate quantitative combinations of aldehydes (A1, A2, and A3) with hydrazines (H1, H2, and H3), as described in Table 2. Each library contains a different combination of three hydrazone products. The hydrazone libraries L1, L2, and L3 are prepared by mixing each aldehyde (A1, A2, or A3) with a mixture of three hydrazines (H1, H2, and H3). Similarly, libraries L4, L5, and L6 are prepared by mixing each hydrazine (H1, H2, or H3) with a mixture of three aldehydes (A1, A2, and A3). A deconvolution process is applied to identify the antibacterial compound in the libraries [25]. Detailed student handouts, notes for instructors, and required materials are provided in Supplementary Materials.



Scheme 1. Condensation reaction between aldehydes (A1, A2 and A3) and hydrazines (H1, H2 and H3) to yield hydrazone derivatives products (P1–P9). The chemical structures are shown in Appendix A.

Table 1. The preparation matrix of the studied hydrazone products P1–P9 [a].

	A1	**A2**	**A3**
H1	P1	P2	P3
H2	P4	P5	P6
H3	P7	P8	P9

[a] Parallel procedure involves nine separate syntheses. The nine compounds of hydrazone products are tested individually in separate wells.

Table 2. The combinations of starting materials yielded compositions of hydrazone libraries L1–L6 [a].

Library Label	**Library Content**	**Starting Materials**			
L1	P1, P4, P7	A1	H1	H2	H3
L2	P2, P5, **P8**	A2	H1	H2	H3
L3	P3, P6, P9	A3	H1	H2	H3
L4	P1, P2, P3	H1	A1	A2	A3
L5	P4, P5, P6	H2	A1	A2	A3
L6	P7, **P8**, P9	H3	A1	A2	A3

[a] Combinatorial procedure involves six separate syntheses. The six libraries are tested as mixtures of three hydrazone compounds in one well. The deconvolution process identifies the antibacterial product by finding the cross between libraries showing antibacterial activity. For example, the product P8 is obtained by the cross between L2 and L6 libraries.

This lab experiment was implemented in the Organic Chemistry Lab course, which was held parallel to the Organic Chemistry 2 and Microbiology courses. Participating students are familiar with aldehyde reactions and have experience with classical microbiology techniques. The lab experiment has three stages: Pre-Lab, Lab-Work, and Post-Lab.

Pre-Lab. The stage comprises three parts. (1) In class meetings of 1 h conducted 10 days before the Lab-Work stage. Students were introduced to the principles of combinatorial synthesis, followed by a template of the experimental layout of the 96-well plate (Figure S1, Supplementary Materials). These included details concerning the nine products, six libraries, two bacterial species, each test with duplicates and controls, and defining the parameters and the basic structure of the two experimental units. Students were also introduced to the multichannel pipette work procedures. (2) Students were required to prepare a Pre-Lab report, including an autonomous assignment to propose a 96-well plate layout defining the lab experiment objective, the materials, and a visualization of the procedure's steps (Student Handout Part A, Supplementary Materials). (3) In an in-class meeting of 1 h conducted 2 days before the Lab-Work stage, students were required to explain orally their experimental design layout of a 96-well plate. This lead to a class discussion, provided a learning feedback cycle, and opened up the dialogue around microbiological tools in the organic chemistry lab.

Lab-Work. This stage was conducted in one session of 3 h. The students performed the experiment according to their choice of design layout for a 96-well plate. Hydrazone synthesis and antibiotic screening procedures are described in Student Handout Parts B and C, Supplementary Materials.

Post Lab. After 24–48 h of incubation, bacteria growth results were collected and presented as described in Student Handout Part D, Supplementary Materials. Finally, students were asked to analyze and evaluate their results. The requests for Post-Lab reports are described in Student Handout Part E, Supplementary Materials. This stage used an additional assessment component to evaluate student interest, engagement, and comprehension.

3. Materials and Methods

3.1. Context and Participants

This laboratory experiment was carried out by second-year undergraduate students in the obligatory Organic Chemistry Laboratory course that fulfills core curriculum college requirements for the biotechnology engineering study program practiced since 2016. Although the experiment involves simple lab techniques, an understanding of the experimental setup is required. The study was carried out from the fall semester of 2022 to the end of the fall semester of 2024. The 96-well plate layouts describing the experimental setup produced by the students were used for analysis and evaluation.

3.2. Research Question

The research question stemmed from the hypothesis that students' experimental designs revealed their bias about the chemistry and microbiology disciplines and led to the following research question: What can be learned about students' disciplinary bias from their choices in designing a free-choice laboratory learning?

3.3. Research Design

A qualitative research methodology was used under the constructivist research paradigm as it explores a phenomenon appearing within a specific context [27]. The research itself was an exploratory case study. Employing the case study approach stemmed from the uniqueness of the specific course and the large body of data that could only be analyzed qualitatively [28]. The existence of a hypothesis concerning the data obtained through the course led to an exploratory approach [29], which can also serve as an educational context [30].

3.4. Research Instrument and Data Collection

The main research instrument was the template design of the 96-well plate along with supporting student explanations regarding the considerations leading to the design (Student Handout Part A, Supplementary Materials). The students presented the template design in the Pre-Lab stage, along with a written explanation relating to their considerations. In addition, students related to their designs during the Lab-Work and the Post-Lab stages. A total of 74 layouts containing plate designs and reflections were obtained and used for the analysis.

3.5. Data Analysis

Credible data analysis in using a constructivist paradigm qualitative approach requires prolonged engagement by the researchers with the data and their interpretation by triangulation that includes a comparison of diverse theoretical perceptions in addition to the data [28]. To extract information from 74 student designs, Braun and Clarks' phases for thematic analysis were employed [31]. This methodology is a flexible analysis system that identifies and categorizes patterns (themes) within a data set. It can be applied in various theoretical frameworks, and the researchers hold an active role in identifying and selecting the themes of interest and reporting them. This flexibility in implementation makes it a useful tool in this research as it employs qualitative data analysis in a non-traditional qualitative analysis data set. The guiding principle behind this type of analysis is to view the accumulated data to discover what information can be derived from it. The first stage is for the researchers to familiarize themselves with the data. The aim is to be immersed within the data to identify patterns. Unlike the traditional use of this methodology in a textual data set, this stage was performed visually. This stage leads to the second phase, in which initial codes are produced, categorizing the interesting aspects and characteristics of the different patterns. The third stage is naming the potential themes and interpreting the initial coding. The fourth stage reviews the hypothesized themes and checks if they are supported by the data within the theme and the total data accumulated. The fifth stage consists of naming and defining the themes, followed by the last stage, which is to report them. Implementing this methodology in this study over a mostly visual data set required a few adaptations.

Initially, the designs were viewed to identify repeating patterns (Figure 1). As this was a non-textual design, patterns were identified visually. The resulting patterns were firstly a separation of the materials or the bacteria, vertically or horizontally. Hence, the initial coding was for materials and bacteria separation (i.e., a disciplinary divide). The resulting themes were further classified visually for patterns, mainly horizontal or vertical designs, which were again categorized, named, and interpreted. In this phase, the interpretation consisted of both analyzing students' reflections as well as the lecturer's input regarding the methods employed by them.

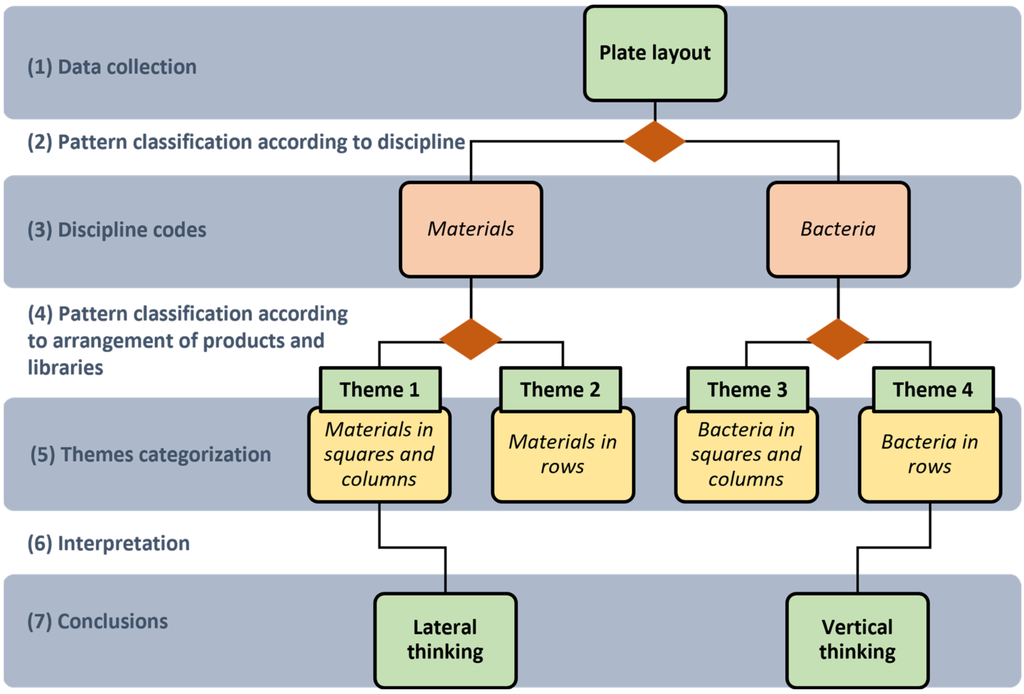


Figure 1. Thematic analysis of students' 96 well-plate designs.

4. Results

The lab experiment, utilizing a 96-well plate accessory, enables lecturers to give students a degree of freedom in designing their experiment setup. The students have to consider multiple experiment parameters, including products (individual compounds), libraries (mixtures of compounds), bacterial species, controls, and replicants.

The consequent assortment of the layouts of 96-well plates (Figure 2) serves as a database for analysis in the current study. The chemical design focus was on separating the products and libraries, whereas the microbiology design revolved around separating the bacterial species. The first of which, classified as material-oriented, shows plate designs created from a chemistry perspective (Figure 2a,b). As can be seen, the plate was divided into products and libraries and then subdivided according to the bacterial species. The second classification focuses on bacteria separation and was classified as bacteria-oriented, accordingly (Figure 2c,d). The plate arrangement features a divide into two halves based on bacteria species i.e., *Escherichia coli* (*E. coli*) and *Bacillus cereus* (*B. cereus*). Each half contained both products and libraries. The 74 plate layouts reviewed yielded 42 *Materials* and 32 *Bacteria* classifications (Figure 3a). These discipline codes' divide reflects stage 3 of the thematic analysis (Figure 1).

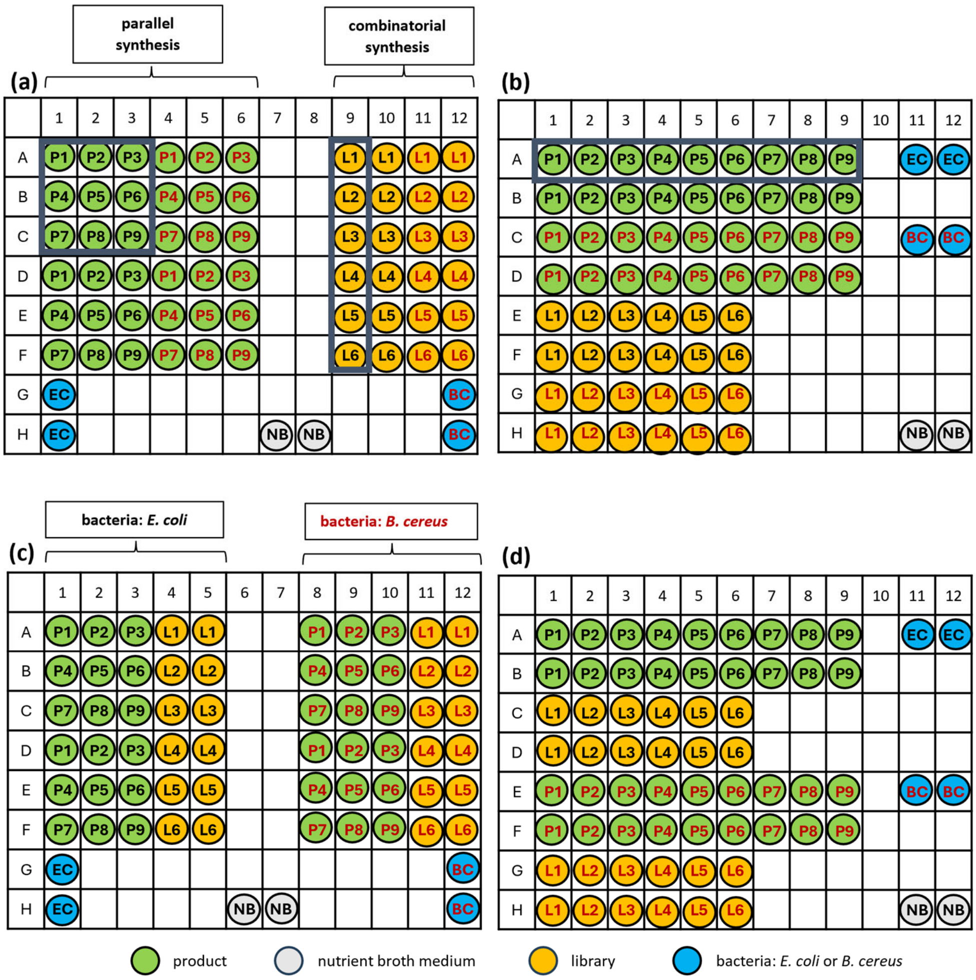


Figure 2. Schematic illustrations of plate layouts. (**a**,**b**) The material-oriented arrangement shows a chemistry viewpoint focused on separating the materials between libraries and products. (**c**,**d**) The bacteria-oriented arrangement shows microbial considerations separating the plate between bacteria. The black and red font colors represent bacterial species *E. coli* and *B. cereus*, respectively. Note: the visual arrangement of products and libraries (**a**,**c**) in squares and columns and (**b**,**d**) in rows.

The next stage, pattern classification, added a dimension relating to the visual arrangement of products and libraries in each of the two previous ones (i.e., materials- and bacteria-oriented). Both classifications share three common visual elements: square, column, and row (Figure 2). The square pattern describes the product (P1–P9) preparation as a 3 by 3 matrix, according to Table 1. The column pattern describes the libraries' (L1–L6) preparation according to Table 2. The row pattern shows the products P1–P9 and libraries L1–L6 on the plate according to their ordinal numbering following the plate numbering of 1–12. The various combinations of the three visual elements resulted in four themes named (1) materials in squares and columns, (2) materials in rows, (3) bacteria in squares and columns, and (4) bacteria in rows (Figures 1 and 2).

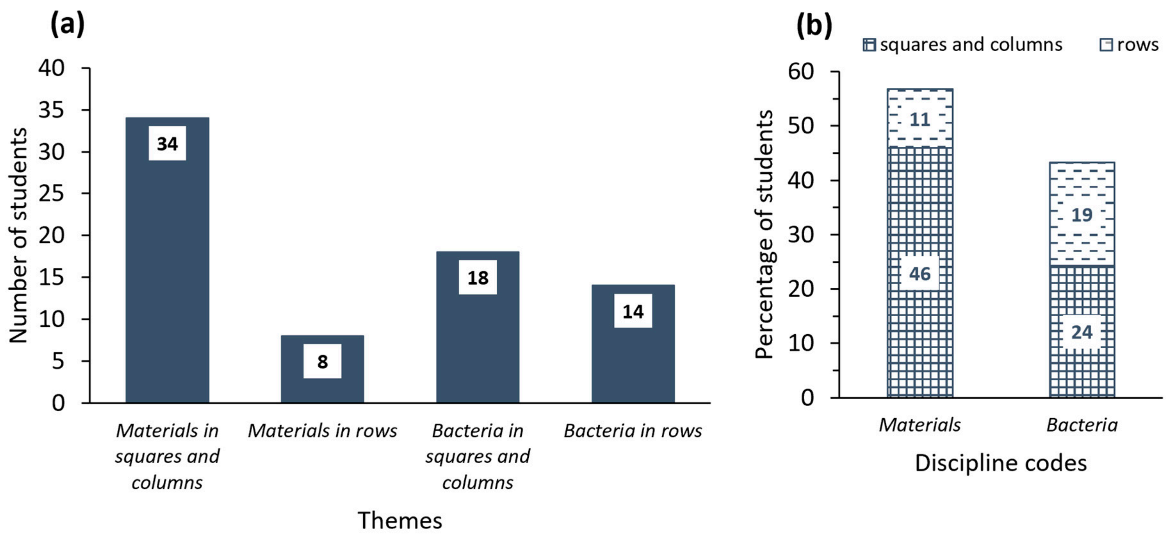


Figure 3. Classifications of plate layouts (n = 74). (**a**) Number of students categorized following theme analysis. (**b**) Percentage of students taking disciplines and visual considerations.

Students' explanations and reflections regarding their design choices were reviewed to interpret the themes obtained. Samples of supporting quotes are arranged according to the themes and provided below.

Theme 1—materials in squares and columns (presented in Figure 2a): Students relate to the preparation of the product as a whole following the product matrix in Table 1. The focus of students is on the methodology of the materials preparation.

- "This way, it will be easy to differentiate between the products and libraries";
- "The products are arranged according to the preparation protocol and the Eppendorf arrangement on the stand";
- "a 6-in-a-column arrangement will be suited for using a multichannel pipette for inserting the bacteria".

Theme 2—materials in rows (presented in Figure 2b): Students focus on the material insertion process as they relate to plate numbering as assistance and enhancement of convenience.

- "Following the numbering will help avoid confusion";
- "We arrange it like this for the convenience of using the multichannel pipette".

Theme 3—bacteria in squares and columns (presented in Figure 2c): The focus of students is on both separating bacteria and preparation of the materials. Therefore, some quotes reflected the ideas expressed in Theme 1. The quotes presented below are those that added biology-related considerations.

- ". . .not to get confused between the bacterium types";
- "Each half is designated for one bacterium type to avoid contamination";
- "It will be easier to interpret the results when each bacterium's effect is shown separately".

Theme 4—bacteria in rows (presented in Figure 2d): The focus of students is on separating the bacterial species along with an emphasis on the material insertion and following the plate numbering for convenience.

- "We choose this arrangement to have a more convenient separation between the bacteria and in order to prevent confusion when arranging the products.";
- "This arrangement is very convenient for the insertion.";
- "This arrangement enables us to remember where we stop. . .the products and libraries numbers match the numbering on the 96-well plate.".

Figure 3 summarizes the results of this study that visually analyzed students' plate layouts (n = 74). Figure 3a shows that Themes 1, 2, 3, and 4 reflected 34, 8, 18 and 14 designs, respectively. The correlation between the disciplines to visual elements revealed in Figure 3b presents that (i) 57% of students showed chemical disciplinary (Materials) orientation and 43% of students showed microbiological disciplinary (Bacteria) orientation. (ii) A total of 70% of students' designs were of Themes 1 (46%) and 3 (24%) and focused on material preparation. (iii) A total of 30% of students' designs were of Themes 2 (11%) and 4 (19%) and focused on the convenience and technical aspects of material insertion.

Among the designs, there were two outstanding plate designs showing a library composition matrix as displayed in Figure 4. The first design divided the plate into four parts, each containing a matrix composed of libraries and products as shown in Figure 4a. The second design turned the 3 by 3 product matrix (Table 1) so that the aldehyde is in the column and the hydrazine is in the row (Figure 4b). This design creates a correlation only between the products and L1, L2, and L3. The students explained their choice by saying that "this array was most effective because it enabled them to see the active compound clearly". These layouts simplified the deconvolution process, resulting in a clear analysis and showing student design focus stemming from the result analysis perspective.

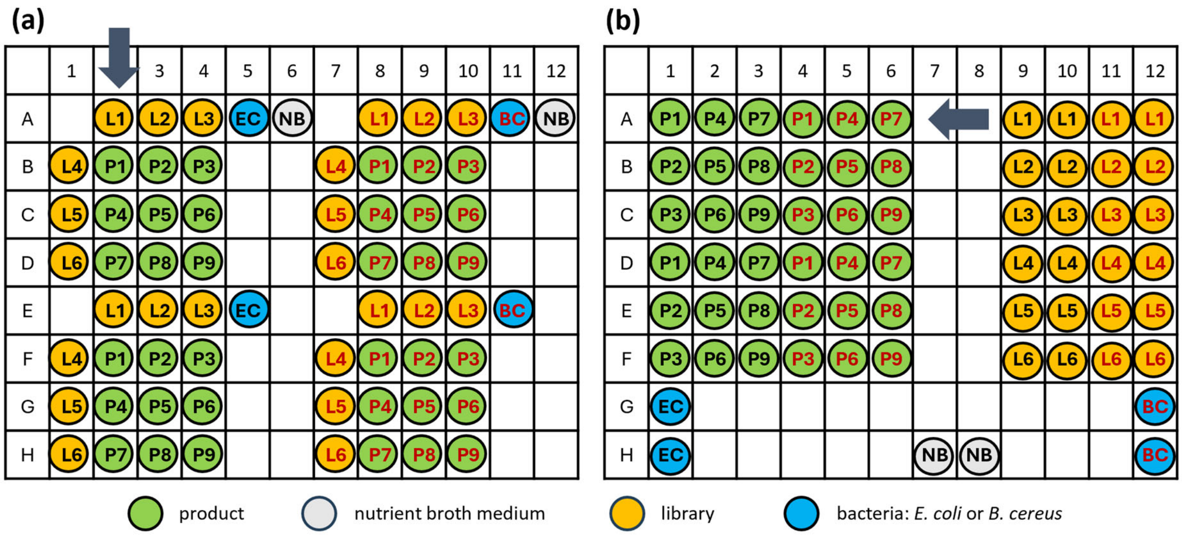


Figure 4. Schematic illustrations of distinctive plate layouts showing the correlation between the products and libraries. (**a**) A matrix composed of libraries and products, all correlating. (**b**) Libraries L1, L2, and L3 correlate with the products. The black and red font colors represent bacterial species: *E. coli* and *B. cereus*, respectively.

The antimicrobial activity was visualized and analyzed after 24–48 h of incubation (Figure 5). Clear liquids were obtained in the wells of the compound P8 (called guanofuracin) due to its inhibitory effect on bacterial growth [32,33]. A similar effect was observed in the wells of the L2 and L6 libraries, which contained the compound P8 (Table 2). Figure 5a,b corresponds with Themes 1 and 3 and how they relate to the way students synthesized the products in a matrix form (Figure 5c). Respectively, Figures 5d and 5f display Themes 2 and 4 as students planned the synthesis of the hydrazone derivatives (P1–P9) ordinally in line (Figure 5e) and mirror-sampled it directly onto the 96-well plate. Hence, we can deduce the connection between the thinking scheme guiding the Pre-Lab product preparation plan and the resulting themes in the plate design; i.e., the thinking schemes dictate the design considerations throughout the lab experiment.

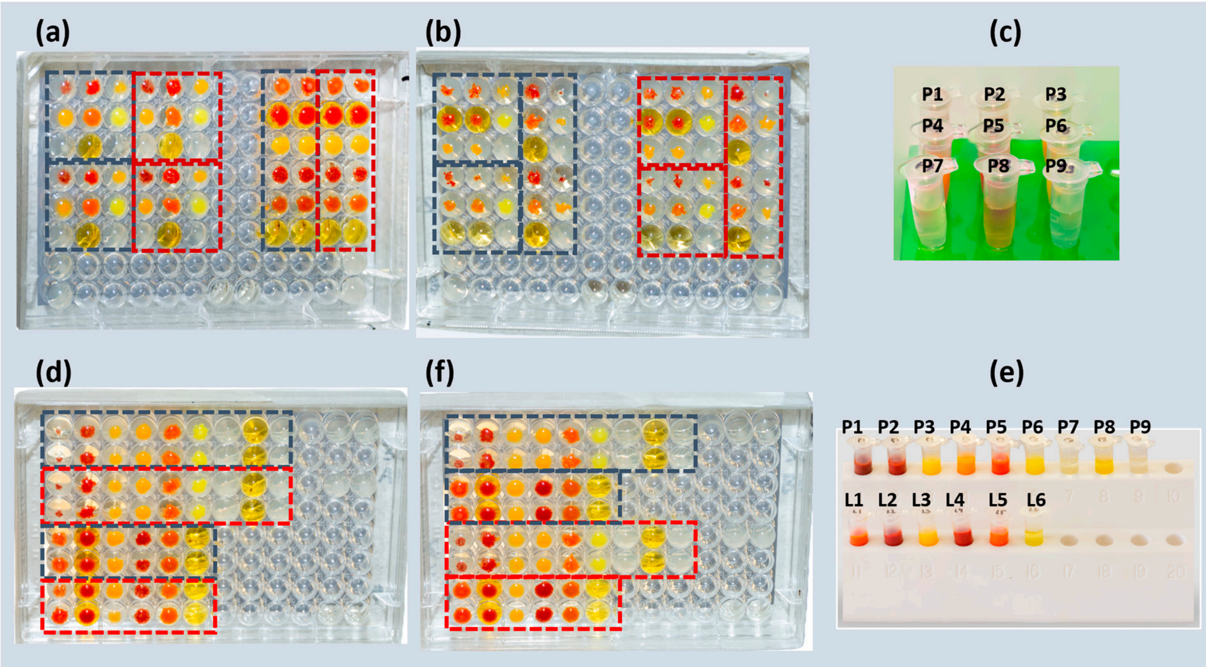


Figure 5. Bottom view of the 96-well plate screening results after 24 h of incubation (the dashed lines represent the series of products and libraries; each color represents a different bacterial species). The 96-well plate designs correspond with (**a**) Theme 1—materials in squares and columns, (**b**) Theme 3—bacteria in squares and columns, which relate to (**c**) the product (P1–P9) square of 3 by 3 Eppendorf tubes that represents the 3 by 3 matrix preparation, (**d**) Theme 2—materials in rows, (**f**) Theme 4—bacteria in rows which relate to (**e**) the in-line ordinal hydrazone (P and L) preparation. Note: photograph (**e**) presents the color of the hydrazone products (P1–P9) and libraries (L1–L6). Each Eppendorf tube P1–P9 contains one product, and each Eppendorf L1–L6 contains one library of three products.

The lab experiment ran smoothly, and students showed competence in carrying out the experiment effectively and safely, organizing and collecting data, and analyzing their results. Students also shared that they acquired new knowledge and skills in antibiotic discovery and that this lab enabled them to examine the connections between organic chemistry and microbiology while developing multidisciplinary skills. Some students failed to explain their proposed arrangement of the 96-well plate. When encouraged to reflect on the reasons for this failure, they expressed frustration over the requirement to create a 'free' experimental design without more concrete guidelines. Technical errors might be expected due to the lab inexperience of undergraduate students (Notes for the instructor and required materials are provided in the Supplementary Materials).

5. Discussion

A hands-on laboratory experiment focusing on an authentic, familiar topic, such as antibiotic drugs, triggers engagement and interest in learners [34–36]. However, this interdisciplinary subject evokes a complexity expressed through all the experiment stages (i.e., design, performance, and analysis). In addition, cognitive obstacles can stem from lecturers holding disciplinary biases that are expressed in their teaching and analysis as demonstrated in other disciplines [37]. To address and overcome the experiment's complexity and to facilitate students' understanding, the experiment employed the 96-well plate design, which allowed the deconstruction and categorization of the experimental design components. The deconstruction was assisted by adding visual elements such as color coding, geometric forms, and patterns, which have been shown to increase learning [38–40]. This deconstruction approach enables science educators to improve their teaching and instructional design [41]. It also enabled the intuitive reconstruction of an autonomous experimental design and the activation of students' individual presuppositions through a highly visual reconstruction process [42].

The main challenge presented in this case study was the assessment of students' disciplinary thinking schemes through the construction of an interdisciplinary learning activity and the development of methodological tools for the task [43]. The first stage in the analysis identified a disciplinary divide between chemistry and microbiology expressed in students' designs. The divide was fairly even between chemistry (57%) and microbiology (43%) orientations (Figure 3b). Although the lab experiment is under the Organic Chemistry Laboratory course, the findings show that some students can use microbiology knowledge and tools given to them in a microbiology course during the same semester. To further understand students' thinking leading to this divide, the next stage of the analysis was held to review students' design choices according to products and libraries arrangement. The resulting themes reflect students' chemical understanding and biological knowledge as well as their interdisciplinary thinking capacity. These three learning components are best expressed in Theme 3, which combines efficient material preparation along with microbiological considerations. Theme 1 maintains the efficiency of the synthesis methodology. However, microbiology is present as a tool serving the chemical outcome; hence, it does not affect the design as there is no separation between the bacterial species. The students in Themes 2 and 4 exhibited another consideration that is detached from the chemical synthesis. The detachment was expressed in their perception of the experiment as a reactions list rather than a parallel synthesis type. The outcome was a row linear representation following the ordinal plate numbering of the products and libraries. However, Themes 2 and 4 differ, as Theme 4 still withheld the microbial learning element and showed separation between the bacterial species.

The interpretation of the row vs. square type arrangements of the products shows two distinct approaches on the part of the students. Students who arrange the products in rows (Themes 2 and 4) see each product synthesis as standing alone. Therefore, the preparation of the nine individual products is performed sequentially and represented in a row following the plate ordinal numbering. In comparison, students who arranged the products in squares (Themes 1 and 3) perceived the nine individual products as a set of chemical reactions that reflects their common denominator. As a result, their preparation was performed in the form of a matrix, which enabled them to synthesize all nine products simultaneously, showing an understanding of Table 1. The differences between the arrangements and approaches suggest two thinking types discussed in pedagogical literature: vertical and lateral thinking [44].

The four themes can be ranked based on higher-order thinking and interdisciplinary considerations presented in students' plate designs, along with the revised Bloom's Taxonomy described in detail by Krathwohl [45]. It combines Bloom's taxonomy with a knowledge dimension scale ranging from functional knowledge followed by conceptual knowledge, procedural knowledge, and ending with metacognitive knowledge. The knowledge dimensions correlate with the cognitive process dimension following the original Bloom's taxonomy from the level of understanding to the level of creativity. The four themes were placed relating to the cross between the two dimensions. Students' advancement on Bloom's Revised Taxonomy is summarized in Table 3. Themes 1, 3, and 4 reside within the expected area of procedural knowledge and its application and analysis, as some students even go towards interdisciplinarity (Theme 3). However, it appears that one-tenth of students in this study remained within the theoretical content knowledge (Theme 2). Thus, the suggested ranking starts from Theme 3 as the highest, followed by Theme 1, Theme 4, and ends with Theme 2. The two outstanding plate designs (Figure 4) showed a unique arrangement that exemplifies a metacognitive perspective in the planning process. This design sets the assessment bar and provides a pedagogical reference scale for learning activity.

Table 3. Summary of the results after cognitive mapping.

Bloom's Taxonomy	Knowledge Dimension	Category
Apply/Analyze	Procedural knowledge	Theme 1
Understanding	Conceptual knowledge	Theme 2
Analyze	Procedural knowledge	Theme 3
Apply	Procedural knowledge	Theme 4
Evaluate	Metacognitive knowledge	Outstanding designs

In summary, interdisciplinary learning activities require a combination of pedagogical elements that reach beyond interdisciplinary cooperation to produce the desired learning outcomes [5]. The various elements are manifested in the initial theoretical framework and the formulation of a task that upholds that framework. There are three pre-conditions for such an activity, which include contextualization, conceptualization, and problem-solving [46]. Contextualizing a learning activity gives it meaning as learners can situate it within their accumulated knowledge, interests, and learning program (e.g., drug discovery). Conceptualization focuses learners on their studies' content and theories that are relevant to the activity at hand (e.g., organic chemistry and microbiology). Both are crucial in order to facilitate engagement in an authentic activity (e.g., the antibiotic discovery experiment), which will most likely involve a goal and obstacles to overcome to reach it (i.e., problem-solving) [4]. Designing a problem-solving learning activity requires the problem to be process-focused, as learning occurs through reflection during the activity and after its completion [47,48]. Accordingly, students can use the 96-well plate layouts as a reflective tool for their understanding of interdisciplinarity.

A problem-oriented learning activity requires a presentation of a problem that can be contextualized and conceptualized. This is conducted by providing the students who participated in the antibiotic discovery laboratory with a sufficient knowledge base related to the activity at hand. Furthermore, the Pre- and Post-Lab reflections, which play a major part in the learning process, required students to possess a metacognitive skill set [49]. The main hurdle lies with reflective modeling as a teaching tool, as it is the least common among other metacognitive teaching tools [38,50]. This means that the scaffolding process of a problem-solving activity must also include the mitigation of metacognition and cross-disciplinary understanding skills [51,52]. It also presents a problem for teachers in assessing the learning process as it is complex and multi-layered [53]. The combination of the above-mentioned elements results in higher engagement on the learners' part as the learning activity becomes authentic and accessible as well as promotes success [4]. It was also shown in other fields that autonomy and metacognitive ability have contributed to students' awareness of learning and success [54]. However, how to assess the actual cognitive development relied on the non-traditional methodology that was employed.

The presented findings are the result of using thematic analysis as a teaching tool, which brought a qualitative approach to assessing a traditionally non-qualitative field. The result was an identification of cognitive patterns in students that allowed the mapping of their interdisciplinary cognitive scheme. While this is not a grading tool or an accurate assessment of academic performance, it is an effective tool that empowers teaching in an interdisciplinary setting.

6. Conclusions

This research study holds three ideas presented in a hands-on organic chemistry laboratory for second-year students of biotechnology engineering. First, the introduction of interdisciplinary thinking at the first stages of an undergraduate program in which a monodisciplinary framework is usually prevalent. This was exhibited as students mostly remained fixated on a specific technical methodology and discipline. A non-traditional approach might serve to release the monodisciplinary structured thinking schemes at early stages. Second, by adapting an experiment to a modern accessory of a 96-well plate, and providing students with autonomy, both students and lecturers gained a macro view of integrating disciplines (e.g., organic chemistry and microbiology). This important teaching element exemplifies the need to consider traditional methodologies from a pedagogical perspective. In this case, it enabled better learning and teaching. Lastly, identifying students' presuppositions and mapping their cognitive scheme advances teaching towards a personalized teaching track and interdisciplinary learning. These ideas lead to recommendations derived from the findings displayed here. On an institutional level, it is highly beneficial to design courses led by lecturers from different yet overlapping disciplines. This will create a pedagogical environment that supports interdisciplinarity. As shown here regarding the identification of the antibiotic compound, there was more than one distinctive route to obtaining the same result and reaching the same conclusion when designing a single laboratory experiment. On the course level, it is essential for lecturers to be exposed to pedagogical and qualitative research methodologies even in fields that are not traditionally related to their core discipline, providing the capacity to approach their teaching from both interdisciplinary and pedagogical perspectives.

7. Research Limitations

As specified, the laboratory experiment was conducted in an Organic Chemistry Lab course. As such, there was an inherent bias towards the chemistry elements despite the biological elements introduced. This was expressed in an overall imbalance in the disciplinary chemistry approach.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci14111176/s1, Supplementary Materials: 1. Student Handout and 2. Notes for Instructor (PDF).

Author Contributions: Conceptualization, N.B., L.I.-K., Y.U. and I.S.W.; methodology, N.B. and I.S.W.; formal analysis, N.B. and I.S.W.; investigation, I.S.W.; writing—original draft preparation, N.B., L.I.-K., Y.U. and I.S.W.; writing—review and editing, N.B. and I.S.W.; visualization, I.S.W.; supervision, I.S.W.; project administration, I.S.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This research was approved by the Research Ethics Committee of Braude College of Engineering. Approval Code: 2023-002, approval Date: 07 May 2023.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

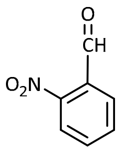
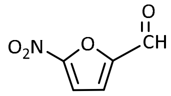
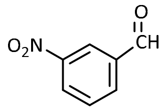
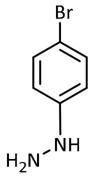
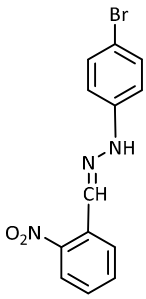
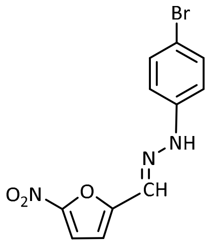
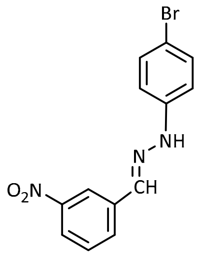
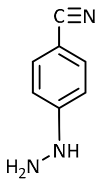
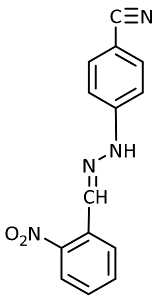
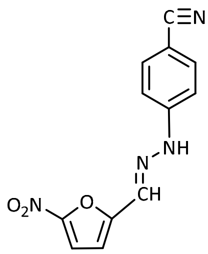
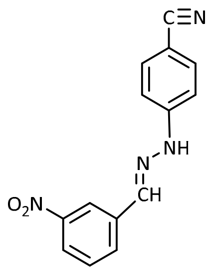
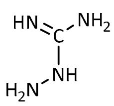
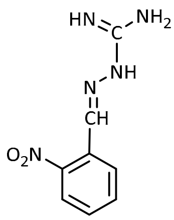
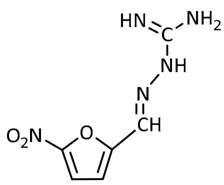
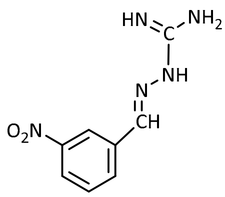
Data Availability Statement: The data analyzed during the study, including the designed layouts and the reflection reports, are not publicly accessible due to the written consent given by the subjects to participate.

Acknowledgments: We are grateful for the generous support from Braude College of Engineering for this study through a Course Development grant (I. S. Weitz).

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Chemical Structures of the aldehyde (A1, A2, and A3), and hydrazine (H1, H2, and H3) starting materials and the hydrazone products (P1–P9).

	 **A1**	 **A2**	 **A3**
 **H1**	 **P1**	 **P2**	 **P3**
 **H2**	 **P4**	 **P5**	 **P6**
 **H3**	 **P7**	 **P8**	 **P9**

References

1. Schmidt, J.C. What is a problem? *Poiesis Prax.* **2011**, *7*, 249–274. [CrossRef] [PubMed]
2. Michelfelder, D.P.; Doorn, N. (Eds.) *The Routledge Handbook of the Philosophy of Engineering*; Routledge: New York, NY, USA, 2020; p. 792.
3. Boon, M.; Van Baalen, S. Epistemology for interdisciplinary research—Shifting philosophical paradigms of science. *Eur. J. Philos. Sci.* **2018**, *9*, 16. [CrossRef] [PubMed]
4. Katz, I.; Assor, A. When Choice Motivates and When It Does Not. *Educ. Psychol. Rev.* **2007**, *19*, 429–442. [CrossRef]
5. Van den Beemt, A.; MacLeod, M.; Van der Veen, J.; Van de Ven, A.; Van Baalen, S.; Klaassen, R.; Boon, M. Interdisciplinary engineering education: A review of vision, teaching, and support. *J. Eng. Educ.* **2020**, *109*, 508–555. [CrossRef]

6. Hardy, J.G.; Sdepanian, S.; Stowell, A.F.; Aljohani, A.D.; Allen, M.J.; Anwar, A.; Barton, D.; Baum, J.V.; Bird, D.; Blaney, A.; et al. Potential for Chemistry in Multidisciplinary, Interdisciplinary, and Transdisciplinary Teaching Activities in Higher Education. *J. Chem. Educ.* **2021**, *98*, 1124–1145. [CrossRef]
7. Gao, X.; Li, P.; Shen, J.; Sun, H. Reviewing assessment of student learning in interdisciplinary STEM education. *Int. J. STEM Educ.* **2020**, *7*, 24. [CrossRef]
8. MacLeod, M.; van der Veen, J.T. Scaffolding interdisciplinary project-based learning: A case study. *Eur. J. Eng. Educ.* **2020**, *45*, 363–377. [CrossRef]
9. Gouvea, J.S.; Sawtelle, V.; Geller, B.D.; Turpen, C. A Framework for Analyzing Interdisciplinary Tasks: Implications for Student Learning and Curricular Design. *CBE Life Sci. Educ.* **2013**, *12*, 187–205. [CrossRef]
10. Oudenampsen, J.; van de Pol, M.; Blijlevens, N.; Das, E. Interdisciplinary education affects student learning: A focus group study. *BMC Med. Educ.* **2023**, *23*, 169. [CrossRef]
11. Abraham, M.R. What Can Be Learned from Laboratory Activities? Revisiting 32 Years of Research. *J. Chem. Educ.* **2011**, *88*, 1020–1025. [CrossRef]
12. Hofstein, A.; Lunetta, V.N. The laboratory in science education: Foundations for the twenty-first century. *Sci. Educ.* **2004**, *88*, 28–54. [CrossRef]
13. Cummins, R.H.; Green, W.J.; Elliott, C.; Lee, D.B.; Le, A.-P.; Edwards, N.Y.; Castillo, F.Y.; Baiamonte, G.; Van Duzor, A.G.; Graham, K.J.; et al. "Prompted" Inquiry-Based Learning in the Introductory Chemistry Laboratory. *J. Chem. Educ.* **2004**, *81*, 239. [CrossRef]
14. Miller, D.M.; Natale, A.; McAnulty, T.K.; Swope, R.D.; McNaughton, E.A.; Beckett, A.; Snoke, H.E.; Schmidt, A.M.; Alumasa, J.N.; Xiong, S. The Design and Implementation of an Interdisciplinary CURE as an Alternative Option for the General Chemistry Laboratory Course. *J. Chem. Educ.* **2022**, *99*, 2530–2540. [CrossRef]
15. Yu, B.; Lu, X.; Chang, J. Multidisciplinary Training for Fostering Next-Generation Medicinal Chemists. *J. Med. Chem.* **2024**, *67*, 17943–17945. [PubMed]
16. Wright, P.M.; Seiple, I.B.; Myers, A.G. The Evolving Role of Chemical Synthesis in Antibacterial Drug Discovery. *Angew. Chem. Int. Ed.* **2014**, *53*, 8840–8869. [CrossRef]
17. Walsh, C.T.; A Wencewicz, T. Prospects for new antibiotics: A molecule-centered perspective. *J. Antibiot.* **2014**, *67*, 7–22. [CrossRef]
18. Whitaker, R.D.; Truhlar, L.M.; Yüksel, D.; Walt, D.R.; Williams, M.D. Synthesis and Biological Testing of Penicillins: An Investigative Approach to the Undergraduate Teaching Laboratory. *J. Chem. Educ.* **2010**, *87*, 634–636. [CrossRef]
19. Ventola, C.L. The Antibiotic Resistance Crisis: Part 2: Management Strategies and New Agents. *Pharm. Ther.* **2015**, *40*, 344–352.
20. Ventola, C.L. The Antibiotic Resistance Crisis: Part 1: Causes and Threats. *Pharm. Ther.* **2015**, *40*, 277–283.
21. Baquero, F.; Levin, B.R. Proximate and ultimate causes of the bactericidal action of antibiotics. *Nat. Rev. Microbiol.* **2021**, *19*, 123–132. [CrossRef]
22. Mathew, B.; Suresh, J.; Ahsan, M.J.; Mathew, G.E.; Usman, D.; Subramanyan, P.N.; Safna, K.F.; Maddela, S. Hydrazones as a Privileged Structural Linker in Antitubercular Agents: A Review. *Infect. Disord. Drug Targets* **2015**, *15*, 76–88. [CrossRef] [PubMed]
23. Verma, G.; Marella, A.; Shaquiquzzaman, M.; Akhtar, M.; Rahmat Ali, M.; Alam, M.M. A review exploring biological activities of hydrazones. *J. Pharm. Bioallied Sci.* **2014**, *6*, 69–80.
24. Thompson, L.A.; Ellman, J.A. Synthesis and Applications of Small Molecule Libraries. *Chem. Rev.* **1996**, *96*, 555–600. [CrossRef]
25. Wolkenberg, S.E.; Su, A.I. Combinatorial Synthesis and Discovery of an Antibiotic Compound. An Experiment Suitable for High School and Undergraduate Laboratories. *J. Chem. Educ.* **2001**, *78*, 784. [CrossRef]
26. Nichols, C.J.; Hanne, L.F. Automated Combinatorial Chemistry in the Organic Chemistry Majors Laboratory. *J. Chem. Educ.* **2010**, *87*, 87–90. [CrossRef]
27. Denzin, N.K.; Lincoln, Y.S. *The SAGE Handbook of Qualitative Research*, 4th ed.; Sage: Thousand Oaks, CA, USA, 2011.
28. Mertens, D. *Research and Evaluation in Education and Psychology: Integrating Diversity with Quantitative, Qualitative, and Mixed Methods*, 5th ed.; Sage: Thousand Oaks, CA, USA, 2019.
29. Yin, R.K. *Case Study Research: Design and Methods*; Sage: Thousand Oaks, CA, USA, 2009.
30. Scanlon, L. *The Role of Research in Teachers' Work: Narratives of Classroom Action Research*; Routledge: Oxfordshire, UK, 2018; pp. 1–143.
31. Braun, V.; Clarke, V. Using thematic analysis in psychology. *Qual. Res. Psychol.* **2006**, *3*, 77–101. [CrossRef]
32. Miura, K.; Reckendorf, H.K. *The Nitrofurans, in Progress in Medicinal Chemistry*; Ellis, G.P., West, G.B., Eds.; Elsevier: Amsterdam, The Netherlands, 1967; pp. 320–381.
33. Le, V.V.H.; Rakonjac, J. Nitrofurans: Revival of an "old" drug class in the fight against antibiotic resistance. *PLoS Pathog.* **2021**, *17*, e1009663. [CrossRef]
34. Freeman, S.; Eddy, S.L.; McDonough, M.; Smith, M.K.; Okoroafor, N.; Jordt, H.; Wenderoth, M.P. Active learning increases student performance in science, engineering, and mathematics. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 8410–8415. [CrossRef]
35. Walker, J.P.; Sampson, V.; Zimmerman, C.O. Argument-Driven Inquiry: An Introduction to a New Instructional Model for Use in Undergraduate Chemistry Labs. *J. Chem. Educ.* **2011**, *88*, 1048–1056. [CrossRef]
36. Agustian, H.Y.; Finne, L.T.; Jørgensen, J.T.; Pedersen, M.I.; Christiansen, F.V.; Gammelgaard, B.; Nielsen, J.A. Learning outcomes of university chemistry teaching in laboratories: A systematic review of empirical literature. *Rev. Educ.* **2022**, *10*, e3360. [CrossRef]

37. MacLeod, M. What makes interdisciplinarity difficult? Some consequences of domain specificity in interdisciplinary practice. *Synthese* **2018**, *195*, 697–720. [CrossRef]
38. El Sayed, K.A.; Chelette, C.T. Laboratory Exercises to Teach Clinically Relevant Chemistry of Antibiotics. *Am. J. Pharm. Educ.* **2014**, *78*, 37. [CrossRef] [PubMed]
39. Choi, J.; Lee, S.E.; Choi, S.; Kang, B.; Kim, S.H.; Bae, J.; Tate, J.A.; Son, Y.-J. Integration of visual thinking strategies to undergraduate health assessment course: A mixed-method feasibility study. *Nurse Educ. Today* **2022**, *113*, 105374. [CrossRef]
40. Galgano, P.D.; Loffredo, C.; Sato, B.M.; Reichardt, C.; El Seoud, O.A. Introducing education for sustainable development in the undergraduate laboratory: Quantitative analysis of bioethanol fuel and its blends with gasoline by using solvatochromic dyes. *Chem. Educ. Res. Pract.* **2012**, *13*, 147–153. [CrossRef]
41. Clark, I.E.; Romero-Calderón, R.; Olson, J.M.; Jaworski, L.; Lopatto, D.; Banerjee, U. "Deconstructing" Scientific Research: A Practical and Scalable Pedagogical Tool to Provide Evidence-Based Science Instruction. *PLoS Biol.* **2009**, *7*, e1000264. [CrossRef] [PubMed]
42. Williams, U.J.; Dries, D.R. Supporting Fledgling Scientists: The Importance of Autonomy in a Guided-Inquiry Laboratory Course. *J. Chem. Educ.* **2022**, *99*, 701–707. [CrossRef]
43. Mansilla, V.B.; Duraising, E.D. Targeted Assessment of Students' Interdisciplinary Work: An Empirically Grounded Framework Proposed. *J. High. Educ.* **2007**, *78*, 215–237. [CrossRef]
44. De Bono, E. *Lateral Thinking: Creativity Step by Step*; Harper & Row: New York, NY, USA, 1970.
45. Krathwohl, D.R. A Revision of Bloom's Taxonomy: An Overview. *Theory Into Pract.* **2002**, *41*, 212–218. [CrossRef]
46. Nikitina, S. Three strategies for interdisciplinary teaching: Contextualizing, conceptualizing, and problem-centring. *J. Curric. Stud.* **2006**, *38*, 251–271. [CrossRef]
47. Silva, T.; Galembeck, E. Developing and Supporting Students' Autonomy to Plan, Perform, and Interpret Inquiry-Based Biochemistry Experiments. *J. Chem. Educ.* **2017**, *94*, 52–60. [CrossRef]
48. Bettencourt, G.M.; Wells, R.S.; Auerbach, S.M.; Fermann, J.T.; Kimball, E. How STEM Undergraduates Choose, Navigate, and Integrate Interdisciplinarity in College and Beyond. *J. High. Educ.* **2023**, *94*, 174–199. [CrossRef]
49. Kipnis, M.; Hofstein, A. The Inquiry Laboratory as a Source for Development of Metacognitive Skills. *Int. J. Sci. Math. Educ.* **2008**, *6*, 601–627. [CrossRef]
50. Zohar, A.; Barzilai, S. A review of research on metacognition in science education: Current and future directions. *Stud. Sci. Educ.* **2013**, *49*, 121–169. [CrossRef]
51. Stentoft, D. From saying to doing interdisciplinary learning: Is problem-based learning the answer? *Act. Learn. High. Educ.* **2017**, *18*, 51–61. [CrossRef]
52. Biggs, J.B.; Tang, C. *Teaching for Quality Learning at University*, 4th ed.; Open University Press: Berkshire, UK, 2011.
53. Ivanitskaya, L.; Clark, D.; Montgomery, G.; Primeau, R. Interdisciplinary Learning: Process and Outcomes. *Innov. High. Educ.* **2002**, *27*, 95–111. [CrossRef]
54. Marantika, J.E.R. Metacognitive ability and autonomous learning strategy in improving learning outcomes. *J. Educ. Learn.* **2021**, *15*, 88–96. [CrossRef]