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Teaching Soil Chemistry through Problematized Experimental Activity: Determination of Acidity, Exchangeable Aluminum, and Available Phosphorus in Soils

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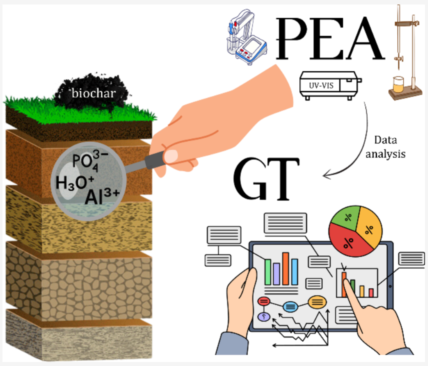

ABSTRACT: This study aims to explore the contributions of problematized experimental activity (PEA) focused on biochar as a sustainable soil conditioner for red-yellow Oxisol in enhancing chemical knowledge in higher education. For this, the theoretical-methodological teaching-learning strategy called PEA was applied, entitled *"Soil chemistry: biochar as a sustainable conditioner"*. The research was conducted with undergraduate Chemistry students during Experimental Inorganic Chemistry I classes at Federal University of Espírito Santo. The students carried out experimental procedures to determine soil's active acidity, potential acidity, exchangeable aluminum, and available phosphorus. Therefore, the potentiometric method, the titrimetric method, and UV−vis spectroscopy were performed. Such techniques involve several objects of knowledge, from the planning of the experimental route and its execution to the interpretation of the results obtained. At the end of the PEA methodological path, the analytical process followed the model of the Grounded Theory in Data. According to the substantive theory developed, the integration of biochar as a sustainable soil conditioner within the PEA framework contributed meaningfully to the development of chemical knowledge, as interpreted through the students' written responses and final synthesis products. The data further revealed the topic's versatility and applicability across varying levels of complexity, allowing the PEA to be adapted to diverse approaches within the same context. These results affirm the PEA's potential as a versatile and impactful pedagogical strategy for fostering both chemical knowledge and practical scientific skills.

KEYWORDS: *Higher Education, Chemical Education, Problem Solving, Agricultural Chemistry, Grounded Theory*

■ INTRODUCTION

Agriculture, essential for human survival, is also a major contributor to environmental degradation.[1] According to the latest survey carried out by the Intergovernmental Panel on Climate Change (IPCC), In Brazil, it accounts for 34.8% of national CO_2 emissions, ranking seventh globally. Contributing factors include fossil fuel use, agricultural waste, and soil management practices.[2,3]

Burning or decomposing agricultural waste and applying $CaCO_3$ for pH correction are major emission sources. Sustainable practices that ensure productivity while reducing environmental impact are crucial to addressing climate change.[4,5]

This study explores biochar as a sustainable alternative in soil management. Produced via pyrolysis of organic matter under low-oxygen and temperature-controlled conditions, biochar emits fewer pollutants and stores carbon that would otherwise be released. Its high stability allows long-term retention of carbon in the soil, reducing CO_2 and CH_4 emissions.[6]

Biochar is a porous, high-surface-area material with strong adsorption capacity, aiding in water and nutrient retention. Its surface contains functional groups that influence soil pH through ion exchange. As pyrolysis temperature rises, acidic groups volatilize, enhancing biochar's performance, especially in acidic soils.[7,8]

Chemistry education can foster reflections on sustainability by using relatable contexts such as soil characterization and biochar. Teaching strategies that develop autonomy, critical thinking, and cognitive skills enhance the relevance and effectiveness of learning.[5,9]

Problematized Experimental Activity (PEA) is a teaching-learning strategy designed to integrate experimental work with meaningful learning, critical thinking, and social relevance. Unlike traditional experimental approaches that often focus on following fixed protocols and verifying expected results, the PEA framework encourages students to engage in complex problem-solving processes. These processes are guided by real-

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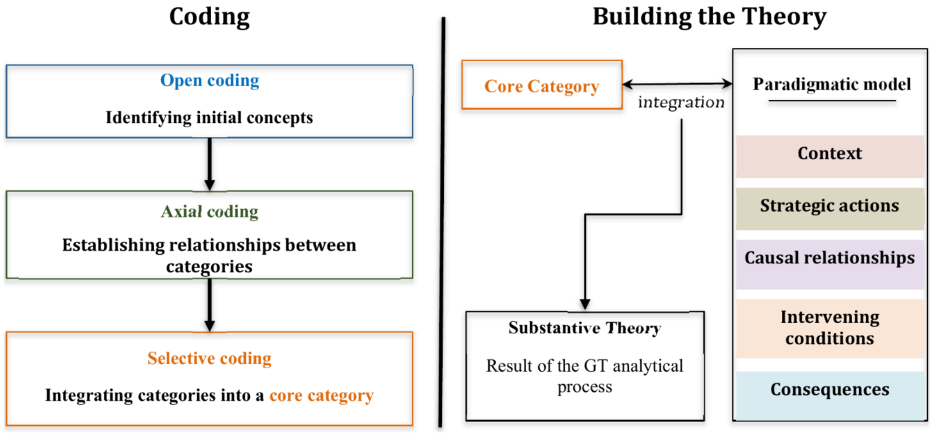


Figure 1. Grounded Theory analytical process applied in this study. The figure illustrates the sequential stages of coding—open, axial, and selective—leading to the identification of the core category. This category serves as the foundation for constructing the substantive theory, organized through a paradigmatic model that includes contextual elements, causal relationships, actions, and outcomes.

world scenarios and structured discussions, fostering autonomy and interdisciplinary connections. One of the distinguishing features of PEA is its incorporation of qualitative assessment tools, such as reflective narratives and collaborative products, which allow educators to evaluate not only content knowledge but also students' ability to interpret data, make informed decisions, and contextualize their learning. These characteristics make PEA particularly useful for promoting higher-order cognitive skills and scientific literacy, thus offering a valuable alternative to conventional laboratory instruction.

It is also structured around both a theoretical and a methodological component.[10,11] The theoretical component involves the definition of (i) the proposed problem, which determines the object or phenomenon of study and the guiding question; (ii) the experimental objective, which outlines what will be empirically investigated; and (iii) the methodological guidelines, which detail the procedural steps necessary to address points (i) and (ii).

The methodological component is organized into five phases:[12]

1. **Initial discussion**: phase of searching for prior knowledge and theoretical foundation.
2. **Organization and development**: elaboration of the experimental guide and execution of the practices.
3. **Return to the work group**: internal discussion of the results.
4. **Socialization**: sharing of the results and impressions among the groups and reviewing of concepts addressed.
5. **Systematization**: elaboration of student synthesis document in which there is integration of existing concepts to form new, more complex and comprehensive concepts.

Through an investigative path aimed at solving theoretical problems, students are provided with the opportunity to engage in critical thinking and collaborative teamwork, skills that are crucial for their future professional endeavors in the field of chemistry. The primary goal of PEA is to support educators in designing and implementing experimental learning activities that promote not only the development of specific chemical knowledge, but also students' ability to critically interpret results and relate them to real-world environmental and social issues. By focusing on qualitative assessment strategies—such as reflective writing, guided protocols, and collaborative synthesis documents—PEA aims to make student reasoning and conceptual integration visible to instructors, while fostering deeper, socially relevant engagement with chemistry content.

Therefore, Grounded Theory (GT) was selected as the analytical methodology for the qualitative data generated through PEA. GT aims to construct a *substantive theory* derived directly from data, offering an interpretive explanation for the investigated phenomenon.[13]

The analytical process in GT follows a structured coding sequence composed of three stages. In the first stage, ***open coding***, the raw data−comprising students' written reflections, observational notes, and their responses to questionnaires−are broken down into discrete parts to identify initial concepts that reflect their meanings.[14] The second stage, ***axial coding***, explores the relationships among these initial categories, grouping them based on similarities and connections to explain underlying patterns. In the final stage, ***selective coding***, the central conceptual framework is formed by integrating categories into broader thematic constructs based on their recurring properties and variations−these are referred to as *dimensions*, representing key traits or aspects of the categories.[15] At this stage, a **core category** is also identified: an abstract and integrative concept that unifies all others within the theoretical structure.[16] Throughout this process, detailed **memos**−reflective and analytical notes−are systematically created by the researchers to track decisions, emerging insights, and methodological reasoning, thus ensuring transparency and rigor in theory construction.

Finally, the development of the **substantive theory** culminates in a **paradigmatic model**, organized around the core category.[17] This model synthesizes the relationships among the analytical categories and maps them onto the educational phenomenon under investigation, providing an interpretive framework that connects students' conceptual development with the broader pedagogical context.[18] This integration provides a cohesive explanation of the phenomenon under investigation. Figure 1 illustrates the coding procedure and the conceptual synthesis that emerges through the core category and paradigmatic model.

This study aims to explore the PEA contributions focused on biochar as a sustainable soil conditioner in enhancing chemical knowledge in higher education. To analyze these contributions, we employed GT following the methodological framework proposed by Strauss and Corbin (2008).[16]

Although biochar was the central theme of this PEA, it is important to clarify that the students did not conduct experimental procedures using soil treated with biochar. The practical activities were limited to the chemical characterization of untreated Red-Yellow Oxisol. The study of biochar's effects was developed through theoretical exploration, analysis of scientific data, and the design of production protocols during the systematization stage. This approach was adopted due to logistical and technical constraints, yet it allowed students to investigate the chemical behavior of soils and reflect on the potential implications of biochar application through contextualized learning.

■ METHODOLOGY

A total of 19 undergraduate chemistry students participated in the set of activities carried out as part of the PEA at the Federal University of Espírito Santo (UFES). The research project was approved by the UFES Research Ethics Committee. Additional ethical details are provided in Supporting Information 1 (SI1). No unexpected or unusually high safety hazards were encountered.

Description of the PEA

The investigation took place in two groups of the *Experimental Inorganic Chemistry* discipline, during the first semester of 2024. Box 1 outlines the theoretical component, with further information provided in SI2.

Box 1. Theoretical Component of the PEA

Proposed Problem Based on soil characterization, how can you define production parameters for biochar suited to your specific soil needs?
Experimental Objective Determine chemical attributes of a red-yellow Oxisol.
Methodological Guidelines Manual of Soil Analysis Methods.[19] Manual of procedures for sampling and chemical analysis of plants, soil and fertilizers.[20]

This component aims to mobilizing knowledge about the chemical elements involved, their role in agricultural soil and the relationships established with biochar. In Box 2, the methodological component is summarized in five step process and their respective actions.

Box 2. PEA Methodological Component

1 Initial Discussion • Reading news via Padlet® • Conversation wheel • Word cloud via Mentimeter® • Theoretical presentation I: soils • Theoretical presentation II: biochar	**2 Organization and development** Carrying out experimental procedures to determine: • Active acidity (SI4) • Potential acidity (SI5) • Exchangeable aluminum (SI6) • Available phosphorus (SI7)
3 Return to the Working Group Internal discussion of the results obtained and construction of the soil technical file.	
4 Socialization General discussion about the results obtained and provided by the researcher and construction of the biochar production protocol.	
5 Systematization Preparation of work linked to the practices carried out, the knowledge mobilized and the discipline syllabus.	

More details about the methodological path are available in SI3. The methodology and materials used in each determination realized during the experimental phase, are listed in SI4−SI7, as shown in Box 2.

Data Collection and Processing Instruments

Experimental cards were distributed (SI8) to the working groups, to initiate critical thinking based on scripted procedures. This material, along with biochar production protocol (SI9) and the student synthesis document related to the discipline syllabus (SI10), were analyzed through GT.

Grounded Theory

The process began with the collection of empirical data, including observational reports, experimental records, protocols for biochar production, and systematized documents—these were created during the final stage of PEA, in which students synthesized the knowledge constructed throughout the activity. Additionally, students responded to experimental cards, which contained open-ended questions designed to elicit reflections on procedures, concepts, and learning outcomes. These cards were prepared by the research team based on the learning objectives defined in the theoretical component of the PEA.

Following data collection, open coding was conducted excerpt-by-excerpt. Axial coding involved reevaluating and refining these initial codes to develop broader, interconnected categories aligned with the study's analytical goals. During selective coding, substantive codes were refined and assigned theoretical significance, leading to the emergence of broader analytical categories. At this stage, the core category was identified, representing the central concept that integrated all others. Throughout each stage was elaborated detailed memos to trace the analytical process. This coding process, summarized in Figure 1, was accomplished using MAXQDA© Analytics Pro, version 24.2.0.[21] All codes were created manually by the research team, with the software serving to organize, retrieve, and visualize the coded data. MAXQDA is a paid qualitative analysis software, available at https://www.maxqda.com, with academic licenses offered at discounted rates. The resulting **substantive theory** explains how engaging in the characterization of soil attributes within the PEA framework promotes the development of chemical knowledge.

■ RESULTS AND DISCUSSION

Student learning was assessed qualitatively through GT, using open, axial, and selective coding of observational reports, written responses, biochar protocols, and synthesis documents. While no quantitative metrics were applied, the coded data revealed conceptual developments aligned with the educational objectives. Open coding produced 53 codes, refined to 21 in axial coding, and grouped into 7 theoretical codes (Box 3).

Box 3. Theoretical Codes and Analytical Categories

Theoretical codes	Analytical categories
C1. Laboratory skills	A1. Laboratory skills
C2. Active acidity	A2. Soil characterization techniques
C3. Potential acidity and exchangeable aluminum	
C4. Phosphorus available	
C5. Acquisition/development of chemical knowledge	A3. Inorganic chemical knowledge
C6. Biochar production parameters and changes in soil chemical attributes	A4. Production parameters and chemical attributes of biochar
C7. Sustainable aspects	A5. Sustainable aspects

The codes in Box 3 represent the most relevant aspects identified in the data. From these, five analytical categories were developed based on recurrence and conceptual consistency.[16] These categories supported the construction of the core category and paradigmatic model. Faculty guided this process, and MAXQDA was used only to organize and visualize the data—not for automatic interpretation.

A1: Laboratory Skills

This category, derived from C1, reflects student behavior during the organization and development phases. Active acidity determination was performed by one group, whose results were shared with others. Most students had no prior experience with a pH meter but quickly learned to calibrate and measure. All groups faced challenges in titrimetric procedures, particularly glassware handling, but each completed multiple titrations, including NaOH standardization, blank tests, and extractor neutralization.

Repetition led to increased autonomy and confidence. Although students were familiar with spectrophotometry, they lacked operational experience and initially struggled with reagent preparation and calibration curve construction, especially adapting calculations for smaller sample sizes. With guidance, both groups adjusted measurements, built accurate calibration curves, and analyzed extracts. This category highlights how PEA supports the development of essential laboratory skills.

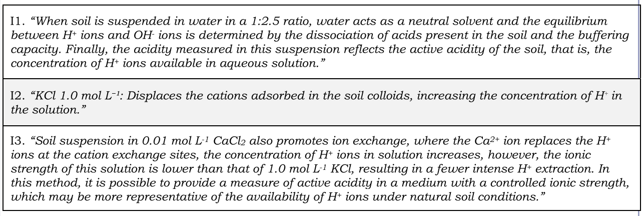
A2: Soil Characterization Techniques

The second analytical category emerged from the integration of C2, C3, and C4 codes, which reflect the interplay between practical skills, theoretical knowledge, and the collaborative sharing of results among groups.

C2 reflects how students interpreted hydronium ion behavior in soil suspensions. They qualitatively assessed differences among three extracts (SI4) using pH values from water, $CaCl_2$, and KCl solutions, recognizing buffering and ion exchange effects.

Although no formal conversion to hydronium ion concentration was performed, students discussed how changes in ionic strength and extractant composition influenced proton availability and the observed pH, reflecting a conceptual understanding of underlying chemical equilibria. This code highlights the importance of connecting experimental observations with theoretical concepts to deepen students' understanding of soil chemistry. Some associated student statements, collected through responses to the experimental cards, are presented in Box 4 as illustrative student responses. In this context, the term "student response" refers to specific excerpts or quotes that reflect students' reasoning and conceptual understanding during the activity, as interpreted through the GT framework.

Box 4. C2 Student Responses



I1. *"When soil is suspended in water in a 1:2.5 ratio, water acts as a neutral solvent and the equilibrium between H^+ ions and OH^- ions is determined by the dissociation of acids present in the soil and the buffering capacity. Finally, the acidity measured in this suspension reflects the active acidity of the soil, that is, the concentration of H^+ ions available in aqueous solution."*

I2. *"KCl 1.0 mol L^{-1}: Displaces the cations adsorbed in the soil colloids, increasing the concentration of H^+ in the solution."*

I3. *"Soil suspension in 0.01 mol L^{-1} $CaCl_2$ also promotes ion exchange, where the Ca^{2+} ion replaces the H^+ ions at the cation exchange sites, the concentration of H^+ ions in solution increases, however, the ionic strength of this solution is lower than that of 1.0 mol L^{-1} KCl, resulting in a fewer intense H^+ extraction. In this method, it is possible to provide a measure of active acidity in a medium with a controlled ionic strength, which may be more representative of the availability of H^+ ions under natural soil conditions."*

The data presented in Box 4 highlight how students chemically differentiated the three suspensions analyzed (SI4). In the determination of pH in soil and water suspensions, the measurement primarily captures the easily dissociable hydronium ions released into the aqueous solution, reflecting immediate acidity. As noted, pH measurements in water are influenced by factors such as the presence of soluble salts and the buffering effects of soil, which include cation exchange reactions and aluminum hydrolysis.[22] This is evident in I1, where students successfully interpreted the chemical mechanisms underlying the analysis in water.

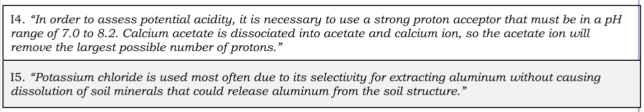
To minimize interferences in pH measurements, saline solutions of $CaCl_2$ and KCl are commonly employed. The Cl^- reduces the soil's buffering capacity by interacting with metallic cations such as Fe^{3+} and Al^{3+}, which undergo hydrolysis in aqueous systems and can affect the results.[23,24] Moreover, Ca^{2+} and K^+ ions participate in cation exchange at adsorption sites in the soil's mineral structure, increasing the availability of H^+ ions in the suspension.[20,24]

The use of 1.0 mol L^{-1} KCl, due to its higher ionic strength, allows for comparative analyses with water measurements, providing insights into the soil's cation exchange capacity and the type of charge present. On the other hand, 0.01 mol L^{-1} $CaCl_2$ offers an electrolyte concentration closer to real soil conditions, making it more representative for studies related to soil fertility.[20,23]

I2 and I3 demonstrate students' ability to link chemical concepts to the use of different suspensions in the method, albeit with varying levels of depth and detail in their explanations. In addition to active acidity, soils also exhibit potential acidity, which encompasses the total H^+ and Al^{3+} content. This potential acidity involves fewer available species that may contribute to increased acidity when released into the environment. These include exchangeable species, which are electrostatically adsorbed to soil colloids, and nonexchangeable hydrogens covalently bonded to the solid phase.[25] Both exchangeable acidity and aluminum are titrimetrically measured, with variations in the choice of extractant.

This analysis underscores the importance of understanding the chemical principles behind soil suspension and pH determinations. It also highlights the potential of enabling students to apply these theoretical concepts in practice. In Box 5, excerpts I4 and I5 illustrate how the choice of extractants influences the determination of potential acidity and exchangeable aluminum.

Box 5. C3 Student Responses



I4. *"In order to assess potential acidity, it is necessary to use a strong proton acceptor that must be in a pH range of 7.0 to 8.2. Calcium acetate is dissociated into acetate and calcium ion, so the acetate ion will remove the largest possible number of protons."*

I5. *"Potassium chloride is used most often due to its selectivity for extracting aluminum without causing dissolution of soil minerals that could release aluminum from the soil structure."*

In I4, the discussion focuses on the function of $Ca(C_2H_3O_2)_2$ during the potential acidity extraction step. The acetate anion, being an efficient proton acceptor, effectively extracts significant amounts of H^+ and Al^{3+} ions. The negative charges generated in this process are balanced by the dissociated Ca^{2+} ions. Due to the buffering capacity of calcium acetate, it does not facilitate the complete extraction of exchangeable aluminum. Consequently, this determination is conducted using a 1.0 mol L^{-1} KCl solution as the extractant.

I5 highlights the chemical role of the KCl extractor in determining exchangeable aluminum. The principle of cation exchange is emphasized, which potassium ions replace exchangeable aluminum ions at the soil's adsorption sites. This student response underlines that the method does not assess the total aluminum content but instead identifies the exchangeable forms available to the soil solution.

In addition to codes C2 and C3, the analytical category also includes C4, referring to the determination of available

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phosphorus by UV−vis spectroscopy. In Box 6, some highlighted student responses are distributed.

Box 6. C4 Student Responses

I6. *“Mehlich-1 is based on extraction by acid solubilization and ion exchange. During the extraction procedure, phosphates are solubilized by* H^+ *ions and* SO_4^{2-} *from the extractant is exchanged with* PO_4^{3-} *adsorbed on the soil with lower binding energy. [...] The pH favors the solubilization of P-Ca forms and small amounts of P-Fe and P-Al. This occurs because* PO_4^{3-} *is a basic anion that readily combines with the* H^+ *ion of Mehlich-1.”*

I7. *"Reagent 725 contains dissolved molybdate and bismuth (III), which form a yellow complex with orthophosphates, a complex that will be reduced by ascorbic acid later, producing a blue complex that will absorb in the 725nm range.”*

I8. *“Molecular absorption spectrometry is based on the interaction between matter and electromagnetic radiation in the ultraviolet or visible light region of the spectrum. Since electrons can absorb photons of specific wavelengths, depending on the molecular orbitals available to carry out electronic transitions, it is possible to measure the absorbance or transmittance of a sample in a specific range or wavelength, if the molecule of interest is already known.”*

I6 illustrates how students comprehended the function of the extractor in determining available phosphorus content. This process begins with the extraction of phosphorus from soil colloids, which was achieved using Mehlich-1 (SI7), a double-acid extractor solution commonly applied in soil characterization in Brazil.[26] In this excerpt, students recognized the importance of pH control and the role of sulfate ions in the extraction process. The SO_4^{2-} competes for adsorption sites, preventing the extracted phosphate from being reabsorbed by the soil.[27] Mehlich-1 maintains the solution pH between 1 and 2, enabling partial solubilization of inorganic colloids through the action of hydronium ions. These ions effectively extract phosphorus from compounds with low binding energy, such as phosphorus bound to calcium. However, due to its limited chemical strength, Mehlich-1 has a reduced capacity to extract phosphorus strongly bound to aluminum or iron oxides in clay minerals.[28]

I7 highlights students’ critical thinking, and their understanding of the analyte preparation steps, particularly the complexation and reduction processes required for spectrophotometric analysis. Students described the preparation of Reagent 725, which involves combining ammonium molybdate ($(NH_4^+)_6Mo7O_{24}\cdot 4H_2O$) and bismuth subcarbonate ($(BiO)_2CO_3\cdot{}^1\!/_2H_2O$) in an acidic system.[29] Following this, the extract and ascorbic acid are added, with the latter reducing the molybdenum−phosphorus complex for measurement.[30]

I8 focused on the principles of the instrumental technique used in phosphorus determination, elucidating key terms such as molecular orbitals and electronic transitions, demonstrating students’ comprehension of the underlying chemical principles. The UV−vis spectroscopy technique involves the interaction of electromagnetic radiation (200−800 nm) with the sample. As the radiation passes through the sample, a portion of the energy is absorbed by the analyte, and the instrument measures transmittance based on the intensity difference.[31]

Both groups responsible for this analysis successfully connected the spectrophotometric measurements to fundamental concepts of light-matter interactions. In summary, this analytical category underscores the educational potential of soil analysis techniques for teaching-learning chemical concepts. These findings highlight the value of practical, inquiry-based activities in fostering a deeper understanding of chemical knowledge while connecting it to real-world applications.

A3: Inorganic Chemical Knowledge

This category emerged from C5 code, which was constructed by integrating codes assigned to the students’ student synthesis documents (i.e., their final syntheses of the activity’s outcomes). As a contextualized teaching-learning strategy diverging from traditional approaches, students were encouraged to produce work connecting the knowledge and techniques developed during the PEA with the syllabus topics for the course (SI10).

Each working group was assigned a specific technique aligned with a corresponding syllabus topic, as summarized in Box 7. The working groups consisted of 4 to 5 students each and were formed within the two regular class sections of the Experimental Inorganic Chemistry course. These are the same student groups referred to earlier in the study.

Box 7. Technique Performed and Syllabus Topic

Technique Performed	Syllabus Topic
Active acidity	Halogen family
Potential acidity	Experiments conducted in class, unrelated to PEA
Exchangeable aluminum	Aluminum family
Available phosphorus	Phosphorus family

These relationships were collaboratively established by the working groups and the head teacher. For instance, the technique for determining active acidity was associated with the halogen family, as the measurements involved soil suspensions containing chloride salts. This task was carried out by a single group, which created a mental map and a report. While the materials included interesting correlations between the technique and the syllabus topic, they lacked more advanced levels of abstraction.

For the determination of potential acidity, the groups chose to create mental maps, but with different emphases. One group focused on concepts related to pH, such as its definition, scale, and colorimetric indicators, as well as their connection to the technique. The second group explored potential acidity by discussing its definition, measurement methods, and influencing factors. Both groups incorporated experiments into their analyses and successfully abstracted the chemical knowledge underlying the selected practices, linking them to the concepts addressed during the PEA.

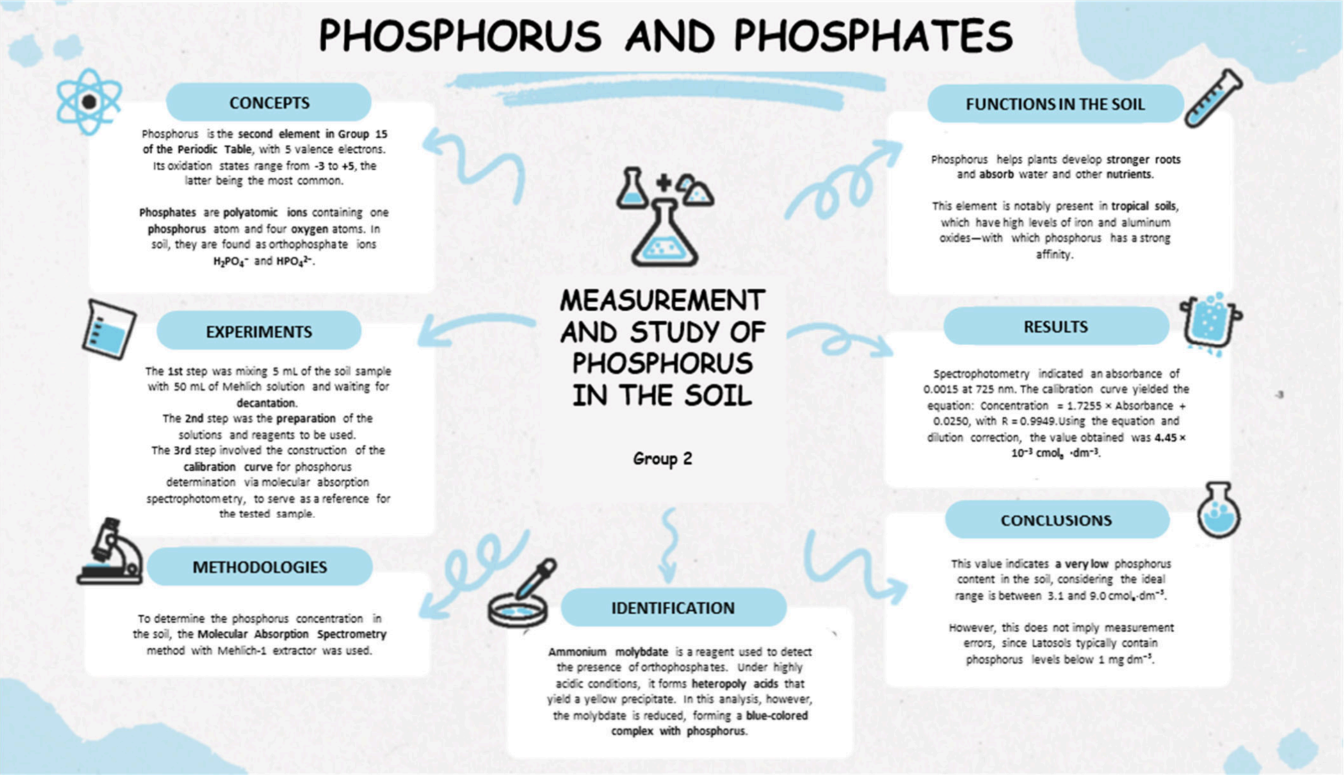
The techniques for determining exchangeable aluminum and available phosphorus were connected to the syllabus topics of the respective periodic families for these elements. For aluminum, one group submitted a detailed written report that addressed all the syllabus points and provided clear and direct relationships to the chemical knowledge used during the investigation. The second group produced a mental map that, while meeting the required objectives, lacked significant depth and abstraction.

Box 8 contains the student responses illustrating the students’ analytical products and their connections between syllabus topics and experimental techniques. These results highlight how contextualized teaching-learning strategies, such as linking analytical techniques to syllabus topics, can foster the

Box 8. C5 Student Responses

I9. *“The soil benefits in several ways from halogens, especially chlorine. The chloride ion* (Cl^-) *is responsible for solubilizing nutrients such as potassium* (K^+) *and sodium* (Na^+)*, making them available to plants and benefiting the soil. This action promotes efficient absorption of nutrients and adjusts the ions in the soil, which is essential for root development.”*

I10. *“Furthermore, the course specifically studied the reaction between tribasic calcium phosphate, which is very sparingly soluble, and sulfuric acid, which caused the solubilization of phosphate in the form of phosphoric acid, forming calcium sulfate in the process. This result corroborated the understanding of how the Mehlich-1 extractor works, since it mainly solubilizes P-Ca, on the one hand, due to the pH, and on the other hand, due to the affinity between sulfate ions and cationic calcium, which is why this extractor overestimates P for some types of soil, in which P-Ca predominates, and underestimates it in others, in which P-Fe or P-Al predominate.”*



PHOSPHORUS AND PHOSPHATES

CONCEPTS

Phosphorus is the **second element in Group 15 of the Periodic Table**, with 5 valence electrons. Its oxidation states range from -3 to **+5**, the latter being the most common.

Phosphates are **polyatomic ions** containing one **phosphorus** atom and four **oxygen** atoms. In soil, they are found as orthophosphate ions $\mathbf{H_2PO_4^-}$ and $\mathbf{HPO_4^{2-}}$.

EXPERIMENTS

The **1st** step was mixing 5 mL of the soil sample with 50 mL of Mehlich solution and waiting for **decantation**.
The **2nd** step was the **preparation** of the solutions and reagents to be used.
The **3rd** step involved the construction of the **calibration curve** for phosphorus determination via molecular absorption spectrophotometry, to serve as a reference for the tested sample.

METHODOLOGIES

To determine the phosphorus concentration in the soil, the **Molecular Absorption Spectrometry** method with Mehlich-1 extractor was used.

MEASUREMENT AND STUDY OF PHOSPHORUS IN THE SOIL

Group 2

IDENTIFICATION

Ammonium molybdate is a reagent used to detect the presence of orthophosphates. Under highly acidic conditions, it forms **heteropoly acids** that yield a yellow precipitate. In this analysis, however, the molybdate is reduced, forming a **blue-colored complex with phosphorus**.

FUNCTIONS IN THE SOIL

Phosphorus helps plants develop **stronger roots** and **absorb** water and other **nutrients**.

This element is notably present in **tropical soils**, which have high levels of iron and aluminum oxides—with which phosphorus has a strong affinity.

RESULTS

Spectrophotometry indicated an absorbance of 0.0015 at 725 nm. The calibration curve yielded the equation: Concentration = 1.7255 × Absorbance + 0.0250, with R = 0.9949.Using the equation and dilution correction, the value obtained was $\mathbf{4.45 \times 10^{-3}\ cmol_c \cdot dm^{-3}}$.

CONCLUSIONS

This value indicates **a very low** phosphorus content in the soil, considering the ideal range is between 3.1 and 9.0 $cmol_c \cdot dm^{-3}$.

However, this does not imply measurement errors, since Latosols typically contain phosphorus levels below 1 mg dm^{-3}.

Figure 2. Mind map created by students (Group 2) as part of the systematization phase of the PEA.

development of chemical knowledge. In particular, they reveal the potential of such approaches to enhance conceptual understanding, promote creativity in presenting relationships, and encourage students to apply chemical concepts in real-world contexts.

The student synthesis documents yielded satisfactory results, based on clarity, coherence, and alignment with syllabus topics. An example of the mind maps developed by the students to connect experimental techniques with syllabus topics is shown in Figure 2, illustrating how the group related the phosphorus determination procedure to both theoretical and practical concepts.

However, the levels of abstraction and correlation varied significantly among the groups working with different techniques. In I9, the group investigating active acidity successfully related the role of the chloride ion to cation exchange processes occurring on the soil's mineral surface.

For the determination of phosphorus, the groups presented their findings in two formats: a mind map (Figure 2) and a text document. The group responsible for the mind map addressed fundamental concepts of phosphorus, described the experimental procedure, and provided a qualitative interpretation of the results. They also included discussions on the role of ammonium molybdate in the analysis and highlighted the importance of phosphorus for plants and its occurrence in the soil. The second group, which submitted a text document, employed a mixed approach that integrated syllabus concepts with phosphorus behavior in the soil. I10 demonstrates how the group connected the course practices with the PEA technique, specifically discussing the operation and limitations of the extractor used.

This analytical category highlights the significant potential of the contextual approach as an alternative for fostering the development of chemical knowledge. While comprehensive theoretical abstractions were not consistently achieved, the results are considered satisfactory given the time constraints of the activity. Furthermore, this study opens possibilities for designing distinct PEAs that focus separately on aluminum and phosphorus, allowing for deeper exploration of these elements.

A4: Production Parameters and Chemical Attributes of Biochar

This analytical category emerged from C6 code and was mainly related to the codifications performed in the biochar production protocol. In general, the protocols were superficial and some presented parameters without any justifications attached. At this point, the role of biochar in the investigation was reassessed. Box 9 shows some student responses related to the biochar production parameters which provide some justification for the choice.

Box 9. C6 Student Responses

I11. *"Heating Rate: 5°C/min until final temperature is reached. A controlled heating rate prevents rapid degradation of the biomass, allowing uniform carbonization."*

I12. *"Final Temperature: 500°C. Temperatures in the range of 400-600°C are ideal for producing biochar with high stability and adsorption capacity."*

I13. *"Surface modification: For this particular protocol, activation with phosphoric acid (H_3PO_4) will be carried out and must be carried out through the following steps: Preparation, impregnation, drying, heating and washing."*

Several protocols included justifications for the chosen parameters, though the level of abstraction varied among the groups. I11 highlights the heating rate parameter, which, notably, was not listed in the production protocol (SI9) and was addressed exclusively by one group. In contrast, I12 focuses on the final temperature parameter. Considering the depth of discussions conducted during the investigation, particularly about the impact of pyrolysis temperature on biochar properties, more advanced responses were anticipated for this parameter. During previous discussion and socialization phases, the influence of pyrolysis temperature on the structural organization of biochar was elucidated. Students explored the effects of pyrolysis temperature, which typically ranges between 300 and 800 °C.[32] Within this range, the carbon matrix of biochar is primarily amorphous, but higher temperatures promote the organization of crystalline regions, aligned in parallel and equidistant arrangements at the nanometer scale.[6] Additionally, higher temperatures facilitate the volatilization of surface functional groups, especially acidic ones, resulting in biochar with a more alkaline pH.[32,33] This property is advantageous for correcting soil acidity.[34] Elevated temperatures increase biochar's surface area, enhancing its cation exchange capacity[35,36] — a crucial factor in preventing the leaching of essential plant nutrients like calcium, magnesium, and potassium.[6,37]

I13 pertains to the surface modification step, an optional stage in the protocol. The group proposed the use of H_3PO_4 as an activating agent in their protocol, based on a literature review conducted during the systematization phase of the activity. However, they did not provide sufficient detail to clarify whether this choice was intended to enhance the material's surface area or increase phosphorus availability. This ambiguity is particularly relevant, given the critical phosphorus levels identified during the soil attribute investigation phase. In the literature, H_3PO_4 is recognized as an effective activating agent due to its lower corrosivity and its ability to produce environmentally safer residues compared to other acids.[38,39] Beyond altering biochar's physical structure, activation with H_3PO_4 induces chemical changes by modifying functional groups, weakening bonds, and forming cross-linked structures.[38,40] These transformations reduce the release of volatile compounds and limit tar formation. Furthermore, H_3PO_4 activation not only enhances porosity but also introduces phosphorus-containing functional groups on the biochar surface, thereby increasing its agronomic value.[41,42]

Although the students did not provide detailed justifications to fully demonstrate signs of learning, their protocols were consistent in terms of parameter selection and combinations. The lack of practical biochar analysis or its application to soil likely affected the depth of the students' responses. These steps were excluded from the PEA due to logistical constraints, as observable changes in soil properties typically require at least 30 days to emerge.

Despite this limitation, the theoretical inclusion of biochar within the PEA provided a valuable opportunity for students to integrate chemical knowledge with environmental awareness. Discussions on biochar as a sustainable agricultural practice during the preliminary phases had a notably positive impact on the students, as evidenced by the frequent mention of sustainability in their protocols.

To further enhance the educational experience, future iterations of the PEA should explore practical ways to incorporate biochar analyses, potentially through shorter-term experiments or simulations. Addressing biochar as a sustainable alternative not only reinforces the contextualization of chemical knowledge but also promotes interdisciplinary learning by connecting chemistry with environmental and agricultural sciences. This foundation is critical for fostering a deeper understanding of both theoretical and practical aspects.

A5: Sustainable Aspects

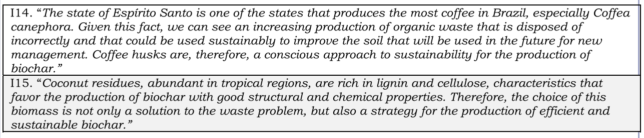
During the preliminary discussion roundtable, students were introduced to news articles highlighting the socioeconomic significance of agriculture and its pivotal role at both state level and national level. The discussion emphasized agriculture's historical relevance to sustaining human life,[1] as well as advancements in agricultural techniques and technologies.[3,6]

In addition to the contributions to economic development, the discussion also addressed the environmental impacts of agricultural practices. These factors underscore the urgent need for sustainable agricultural practices that not only enhance productivity but also ensure food security while mitigating the effects of climate change.[5]

The introduction of biochar as a sustainable soil management alternative was particularly impactful for the participants. Biochar was presented as a promising strategy to improve soil quality, reduce GHG emissions, and promote efficient waste management by repurposing agricultural residues. This approach resonated with students, as reflected in their engagement with sustainability concepts during subsequent activities.

Box 10 highlights student responses associated with Code C7, where students justified their choices of biomass for biochar production based on waste management principles.

Box 10. C7 Student Responses



I14. "*The state of Espírito Santo is one of the states that produces the most coffee in Brazil, especially Coffea canephora. Given this fact, we can see an increasing production of organic waste that is disposed of incorrectly and that could be used sustainably to improve the soil that will be used in the future for new management. Coffee husks are, therefore, a conscious approach to sustainability for the production of biochar.*"

I15. "*Coconut residues, abundant in tropical regions, are rich in lignin and cellulose, characteristics that favor the production of biochar with good structural and chemical properties. Therefore, the choice of this biomass is not only a solution to the waste problem, but also a strategy for the production of efficient and sustainable biochar.*"

In I14 and I15, participants drew connections between the productivity of two distinct crops and the generation of organic waste, advocating for biochar production as a sustainable waste management strategy. Additionally, during the socialization stage—where students collaborated to develop the biochar production protocol—the discussion often revisited the concept of carbon sequestration as a critical approach to mitigating climate change.

A key advantage of biochar is its ability to convert a significant portion of biomass into stable fixed carbon, which resists to microbial decomposition. Soil, as the largest reservoir of organic carbon, plays a central role in the global carbon cycle.[43,44] When applied to soil, biochar has the potential to sequester carbon in resistant forms to microbial degradation, remaining stable for extended periods.[32,45] This unique property underscores biochar's potential contribution to long-term carbon storage and climate change mitigation efforts.

Biochar application into soil is challenging, once its removal is impractical, making the initial characterization of the material and the study of its effects critical. Variations in biomass sources and production parameters result in biochars with distinct properties, meaning not all biochars produce positive results for the soil, emphasizing the importance of careful study.[35,45]

The emergence of this category reflects the relevance of sustainable practices to research participants. Sustainability was integrated throughout the PEA, functioning not only as a contextual framework but also as a platform for cultivating critical, and environmentally conscious scientific thinking.

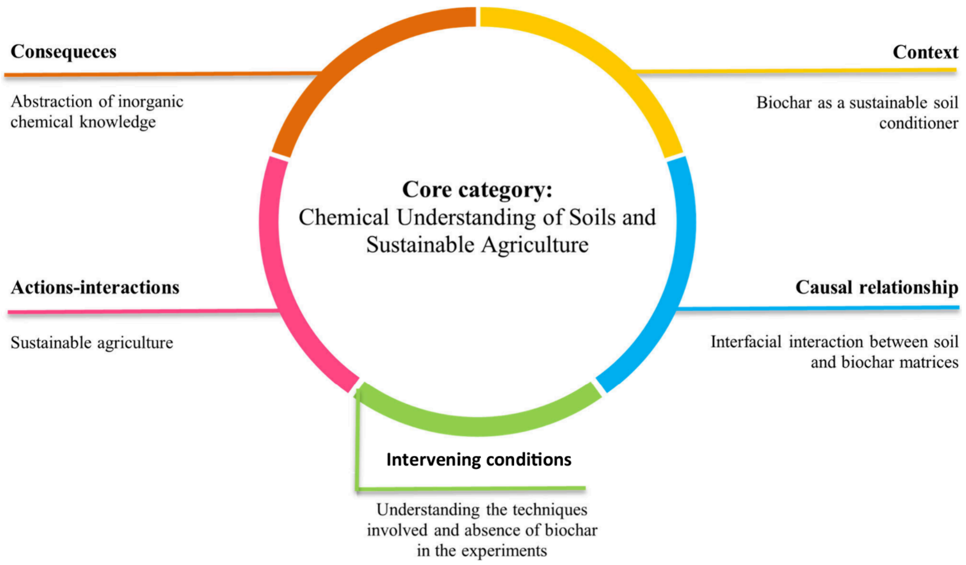


Figure 3. Paradigmatic model and central category used in the development of substantive theory.

Substantive Theory: Soil Chemistry for Mobilization of Inorganic Knowledge

To develop a substantive theory, the central category must effectively integrate the other categories while remaining grounded in the collected data and the phenomenon under investigation. Following this approach, the analytical categories that emerged were applied to the paradigmatic model, leading to the identification of the core category.

The phenomenon under investigation centered on the use of soil chemistry as a means to integrate inorganic chemical knowledge. From this analysis, the core category "Chemical Understanding of Soils and Sustainable Agriculture" emerged and is illustrated in Figure 3. By establishing connections with the paradigmatic model, this category formed the foundation of the substantive theory. Its development sought to address the research question: "How can the characterization of soil chemical attributes contribute to knowledge development?"

The understanding of analytical techniques was identified as an intervening condition in this process, fostering the development of laboratory skills and critical thinking among students. Data collected from experimental records revealed that participants successfully assimilated concepts related to the extraction techniques employed, including the role of extractants in ion exchange processes. Additionally, students provided meaningful interpretations of the chemical reactions involved in complex formation and titration methods, demonstrating a clear grasp of these processes.

The category's contextual framework was rooted in the use of biochar as a sustainable soil conditioner. While sustainable agriculture served as a critical interaction strategy, the absence of biochar in the experimental procedures—previously established as a constraint—emerged as another intervening condition. Analysis of biochar production protocols revealed that students did not develop advanced abstractions about the effects of production parameters on the material's properties. The assessment of students' biochar protocols focused on the scientific justification provided for each selected parameter. While most groups completed the protocols structurally, the depth of chemical reasoning and explicit references to the effects of production parameters were often limited. This conclusion was based on a qualitative analysis in which students' choices were interpreted in light of established literature on agricultural biochar. Although no formal rubric was used, the coding process of GT—particularly open and axial coding—allowed the identification of gaps in abstraction and conceptual integration.

Nonetheless, students were able to establish causal relationships throughout the investigation. These included the interfacial interactions between biochar and soil minerals, as well as the influence of the material characteristics on these interactions. As a result, they developed an understanding of how biochar alters soil chemical attributes and emphasized its significance in sustainable agriculture, particularly in waste management and climate change mitigation through CO_2 sequestration.

The investigation also enabled the development of both theoretical and practical chemical knowledge, particularly regarding titrimetric, UV−vis spectroscopy, and potentiometric methods. Importantly, students successfully linked the topics explored during the PEA to the syllabus and experiments of the applied subject. Student synthesis documents revealed knowledge about the chemical forms of aluminum and phosphorus in the soil and the influence of pH on these attributes.

Thus, the characterization of soil chemical attributes, contextualized within sustainable agriculture and the application of biochar, demonstrates its potential as an effective tool for knowledge development. Future research could explore the potential of each technique used in this investigation individually. For example:

- The determination of active and potential soil acidity, along with exchangeable aluminum content, offers opportunities to address foundational concepts such as chemical calculations, hydrolysis equilibrium, and neutralization reactions, as well as more advanced topics like aluminum complexes and their mineralogical significance.

- The determination of available phosphorus provides a pathway to engage with coordination chemistry and deepen understanding of UV−vis spectroscopy techniques.

These findings highlight the potential of soil chemistry as a rich, interdisciplinary context for teaching-learning, promoting both scientific knowledge and environmental responsibility.

■ CONCLUSIONS

According to the substantive theory, the integration of biochar as a sustainable soil conditioner within the PEA framework contributed meaningfully to the development of chemical knowledge. The analytical process guided by GT highlighted the enhancement of laboratory skills by introducing experimental practices to which participants had little or no prior exposure. Moreover, the theoretical foundation underlying the techniques and the chemistry of the analyzed attributes facilitated the integration of existing knowledge into the development of more complex and comprehensive concepts.

The data further revealed the topic's versatility and applicability across varying levels of complexity, allowing the PEA to be adapted to diverse approaches within the same context. Among the experimental practices, phosphorus determination stood out for its strong potential in fostering knowledge abstraction. This activity provided a basis for exploring key concepts such as ion exchange, UV−vis spectroscopy, and complexation reactions. Similarly, the determination of exchangeable aluminum and its impact on soil pH proved valuable for engaging with topics like stoichiometric calculations, chemical equilibrium, solubility, titrimetric, and the elemental characteristics of aluminum.

It is important to note that the absence of biochar in the experimental process was an intervening condition that limited the ability to correlate production parameters with the material's properties. To address this, future iterations of the PEA should incorporate biochar into the experimental investigations, allowing for a more holistic exploration of its characteristics and applications.

This finding underscores the value of the PEA in enhancing the teaching-learning process through experimental integration, as well as its potential as a versatile and impactful pedagogical strategy for fostering both chemical knowledge and practical scientific skills.

Given its structure, the PEA developed in this study can be adapted to various chemistry curricula, offering instructors a replicable framework to integrate experimental learning, contextual problem-solving, and qualitative assessment.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.5c00027.

Ethical aspects and approval details of the research project (SI1). Theoretical axis of the Problematized Experimental Activity (PEA) (SI2). Methodological axis of the PEA, including description of activities, analytical determinations, and student engagement (SI3). Experimental protocols for soil analysis: active acidity (potentiometric method, SI4), potential acidity (titrimetric method, SI5), exchangeable aluminum (titrimetric method, SI6), and available phosphorus (UV−Vis spectroscopy, SI7). Experimental cards with guiding questions for soil acidity and phosphorus determinations (SI8). Biochar production protocol template (SI9). Course syllabus content related to the activity (SI10) (PDF)

Ethical aspects and approval details of the research project (SI1). Theoretical axis of the Problematized Experimental Activity (PEA) (SI2). Methodological axis of the PEA, including description of activities, analytical determinations, and student engagement (SI3). Experimental protocols for soil analysis: active acidity (potentiometric method, SI4), potential acidity (titrimetric method, SI5), exchangeable aluminum (titrimetric method, SI6), and available phosphorus (UV−Vis spectroscopy, SI7). Experimental cards with guiding questions for soil acidity and phosphorus determinations (SI8). Biochar production protocol template (SI9). Course syllabus content related to the activity (SI10) (DOCX)

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■ REFERENCES

(1) Lima, J. S. G. History of Agriculture in the World: From the Neolithic to the Contemporary Crisis. *Science and Culture.* **2017**, *69* (2), 51.

(2) Climate Watch Data. Greenhouse Gas (GHG) Emissions. https://www.climatewatchdata.org/ghg-emissions (accessed Dec 2024).

(3) Silva, C. F. E. *Socio-ecological resilience of agroecosystems with different types of management in the semi-arid region of Pernambuco*; Federal University of Pernambuco: Pernambuco, 2017; pp 68.

(4) Sajid, M. J.; Rahman, M. H. Ur. The Nexus between Environmental Impact and Agricultural Sector Linkages: A Case Study of Pakistan. *Atmosphere.* **2021**, *12* (9), 1200.

(5) Ribeiro, D. d C. de A.; Salgado, T. D. M.; Sirtori, C.; Passos, C. G. Sustainability and Environmental Education in the Teaching of Chemistry: contributions to raising awareness about sustainable agriculture. *New Chemistry at School.* **2022**, *44* (2), 160−172.

(6) Lehmann, J.; Joseph, S. *Biochar for Environmental Management*, 1st ed.; Earthscan: London, 2009; pp 416.

(7) Petter, F. A.; Lima, L. B. de; Morales, M. M.; Maimon Júnior, B. H.; Morais, L. A. de. Biochar in soil: agronomic and environmental aspects. *International conference on sustainable agriculture.* **2016**, 73−81.

(8) Tusar, H. M.; Uddin, Md. K.; Mia, S.; Suhi, A. A.; Wahid, S. B. A.; Kasim, S.; Sairi, N. A.; Alam, Z.; Anwar, F. Biochar-acid soils interactions—a review. *Sustainability.* **2023**, *15* (18), 13366.

(9) Rodrigues, N. C.; Correia, D. *The chemistry of soils: a perspective of active learning*; Federal University of Mato Grosso do Sul: Campo Grande, 2022; pp 99.

(10) Ausubel, D. P; Novak, J. D.; Hanesian, H. *Educational psychology: a cognitive view*, 2nd ed.; Holt, Rinehart & Winston: New York, 1968.

(11) Abscal, G. C.; Silva, A. L. S. da; Ribas, S. N. Teaching chemistry via Problematized Experimental Activity (PEA): narrative analysis of an investigation-research. *CIMEAC Notebooks.* **2024**, *14* (1), 145−160.

(12) Ferreira, M.; Silva, A. L. S. da; Silva Filho, O. L. da; Portugal, K. O. Problematized Experimental Activity (PEA): Praxiological and pedagogical assertions to the experimental teaching of sciences. *Research in Science Teaching.* **2022**, *27* (1), 308−322.

(13) Birks, M.; Mills, J. Grounded Theory: A practical guide. *QMiP Bulletin.* **2024**, *1* (37), 59−63.

(14) Charmaz, K. *The construction of grounded theory: a practical guide to qualitative analysis*, 1st ed. Artmed: Porto Alegre, 2009; pp 272.

(15) Charmaz, K.; Thornberg, R. The pursuit of quality in grounded theory. *Qualitative Research in Psychology.* **2021**, *18* (3), 305−327.

(16) Corbin, J.; Strauss, A. *Basics of Qualitative Research: Techniques and procedures for developing grounded theory*, 4th ed.; SAGE: United States of America, 2015; pp 434.

(17) Zhang, F.; Peng, X.; Huang, L.; Liu, Y.; Xu, J.; He, J.; Guan, C.; Chang, H.; Chen, y. A caring leadership model in nursing: A grounded theory approach. *Journal of Nursing Management.* **2022**, *30* (4), 981−992.

(18) Medeiros, A. P. de; Santos, J. L. G. d; Erdmann, R. H. The grounded theory in research in administration: evidence and reflections. *Journal of Management Sciences* **2019**, *21* (54), 95−110.

(19) Teixeira, P. C.; Donagemma, G. K.; Fontana, A.; Teixeira, W. G. *Manual of Methods of Analysis of Solo*, 3rd ed.; Embrapa: Brasília, 2017; pp 577.

(20) Meneghetti, A. M. *Manual of Procedures for Sampling and Chemical Analysis of Plants, Soil and Fertilizers*, 1st ed.; EDUTFPR: Curitiba, 2018; pp 252.

(21) *MAXQDA ANALYTICS PRO, version 24.2.0 [software]*. VERBI, Berlin, Germany, 2023. https://maxqda.com.

(22) Silva, F. C. *Manual of chemical analysis of soils, plants and fertilizers*, 2nd ed.; Embrapa: Brasília, 2009; pp 627.

(23) Brady, N. C.; Weil, R. R. *Elements of Nature and Soil Properties*, 3rd ed.; Bookman: Porto Alegre, 2013; pp 716.

(24) Takamoto, A.; Takahashi, T.; Togami, K. Estimation models from soil pH with a solid-to-liquid ratio of 1:2.5 to pH measured by other methods using soils in Japan. *Soil Science and Plant Nutrition.* **2023**, *69* (3), 190−198.

(25) Kunz, K. M. *Estimation of potential acidity in soils using Vis-NIR spectroscopy*; Federal University of Santa Maria: Rio Grande do Sul, 2022; pp 52.

(26) Assunção, D. B.; Silva, F. A. N. Chemical analysis of the soil and the quality control of the laboratories. *Trópica Journal - Agrarian and Biological Sciences.* **2013**, *6* (3), 120−136.

(27) Freitas, I. F.; Novais, R. F.; Villani, E. M. de A.; Novais, S. V. Phosphorus extracted by ion exchange resins and mehlich-1 from oxisols (latosols) treated with different phosphorus rates and sources for varied soil-source contact periods. *Brazilian Journal of Soil Science.* **2013**, *37* (3), 667−677.

(28) Santos, L. da S. *Variability of extracted phosphorus caused by analytical variation in the Mehlich-1 and 3 methods*; Federal University of Santa Maria: Rio Grande do Sul, 2013; pp 80.

(29) Zhai, Q.-Z. Determination of phosphorus by phosphorus molybdenum blue spectrophotometry by bismuth antimony sensitization. *Bulletin of the Chemical Society of Ethiopia.* **2023**, *37* (6), 1307−1313.

(30) Filho, H. B.; Krug, F. J.; Zagatto, E. A. G.; Rocha, F. R. P. *Ultraviolet and Visible Spectrophotometry*; University of São Paulo: São Paulo, 2010; pp 22.

(31) Joseph, S.; Cowie, A. L.; Van Zwieten, L.; Bolan, N.; Budai, A.; Buss, W.; Cayuela, M. L.; Graber, E. R.; Ippolito, J. A.; Kuzyakov, Y.; Luo, Y.; Ok, Y. S.; Palansooriya, K. N.; Shepherd, J.; Stephens, S.; Weng, Z. H.; Lehmann, J. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy.* **2021**, *13* (11), 1731−1764.

(32) Kwapinski, W.; Byrne, C. M. P.; Kryachko, E.; Wolfram, P.; Adley, C.; Leahy, J. J.; Novotny, E. H.; Hayes, M. H. B. Biochar from Biomass and Waste. *Waste and Biomass Valorization.* **2010**, *1* (2), 177−189.

(33) Acharya, N.; Vista, S. P.; Shrestha, S.; Neupane, N.; Pandit, N. R. Potential of Biochar-Based Organic Fertilizers on Increasing Soil Fertility, Available Nutrients, and Okra Productivity in Slightly Acidic Sandy Loam Soil. *Nitrogen.* **2023**, *4* (1), 1−15.

(34) Alkhasha, A.; Al-Omran, A. Evaluating the Effects of Biochar and SAP Polymer on Soil Physical Quality Indices. *Communications in soil science and plant analysis.* **2020**, *51* (8), 1123−1135.

(35) Allohverdi, T.; Mohanty, A. K.; Roy, P.; Misra, M. A Review on Current Status of Biochar Uses in Agriculture. *Molecules.* **2021**, *26* (18), 5584.

(36) Mai, N. T.; Nguyen, A. M.; Pham, N. T. T.; Nguyen, A. T. Q.; Nguyen, T. T.; Do, C. L.; Nguyen, M. H.; Dultz, S.; Nguyen, M. N. Colloidal interactions of micro-sized biochar and a kaolinitic soil clay. *Science of The Total Environment.* **2020**, *738*, 139844.

(37) Cuba, R. M. F.; Paula, B. M. de; Vale, G. B. do; Braga, T. C.; Terán, F. J. C. Activated biochar produced from anaerobic sludge from wastewater treatment plant for removal of tartrazine dye. *Matéria (Rio J).* **2021**, *26* (4), 13109.

(38) Sajjadi, B.; Zubatiuk, T.; Leszczynska, D.; Leszczynski, J.; Chen, W. Y. Chemical activation of biochar for energy and environmental applications: a comprehensive review. *Reviews in Chemical Engineering.* **2019**, *35* (7), 777−815.

(39) Aliakbari, Z.; Younesi, H.; Ghoreyshi, A. A.; Bahramifar, N.; Heidari, A. Production and Characterization of Sewage-Sludge Based Activated Carbons Under Different Post-Activation Conditions. *Waste and Biomass Valorization.* **2018**, *9*, 451−463.

(40) Puziy, A. M.; Poddubnaya, O. I.; Gawdzik, B.; Tascón, J. M. D. Phosphorus-containing carbons: Preparation, properties and utilization. *Carbon.* **2020**, *157*, 796.

(41) Yang, H.; Chen, P.; Chen, W.; Li, K.; Xia, M.; Xiao, H.; Chen, X.; Chen, Y.; Wang, X.; Chen, H. Insight into the formation mechanism of N, P co-doped mesoporous biochar from H_3PO_4 activation and NH_3 modification of biomass. *Fuel Process. Technol.* **2022**, *230*, 107215.

(42) Li, H.; Li, M.; Fu, Q.; Cao, K.; Liu, D.; Li, T. Optimization of biochar systems in the water-food-energy-carbon nexus for sustainable circular agriculture. *Journal of Cleaner Production.* **2022**, *355*, 131791.

(43) Oliveira, E. S.; Reatto, A.; Roig, H. L. Soil Carbon Stocks According to Landscape Components. *Science & Technology Notebooks.* **2015**, *32* (1), 71−93.

(44) Brassard, P.; Godbout, S.; Raghavan, V. Soil biochar amendment as a climate change mitigation tool: Key parameters and mechanisms involved. *Journal of Environmental Management.* **2016**, *181*, 484−497.

(45) Brtnicky, M.; Datta, R.; Holatko, J.; Bielska, L.; Gusiatin, Z. M.; Kucerik, J.; Hammerschmiedt, T.; Danish, S.; Radziemska, M.; Mravcova, L.; Fahad, S.; Kintl, A.; Sudoma, M.; Ahmed, N.; Pecina, V. A critical review of the possible adverse effects of biochar in the soil environment. *Science of The Total Environment.* **2021**, *796*, 148756.