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Bridging biotechnology and sustainability: An inquiry-based STEM activity using enzyme-assisted pectin extraction

Bakhytzhan Temirkhan [1*], Kalampyr Zhumagulova [1], Tolegen Dosmail [2], Assem Abiltayeva [3], Massimzhan Velyamov [4]

[1] Abai Kazakh National Pedagogical University, Almaty, KAZAKHSTAN
[2] Kazakh National Women's Pedagogical University, Almaty, KAZAKHSTAN
[3] Almaty Humanitarian-Economic University, Almaty, KAZAKHSTAN
[4] Kazakh Research Institute of Processing and Food Industry, Almaty, KAZAKHSTAN

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Abstract
The growing emphasis on integrated STEM education and education for sustainable development calls for authentic classroom experiences that connect biotechnology, quantitative reasoning, and real-world environmental issues. This study presents and examines an inquiry-based instructional activity in which students conducted enzyme-assisted pectin extraction from carrot pomace within a food waste valorization framework. Implemented in a regular classroom setting, the activity was designed to engage students in authentic scientific practices, including experimental design, data collection, quantitative analysis, and evidence-based interpretation. Student worksheets which included calculations, graphical outputs, and written reflections, were analyzed to evaluate procedural feasibility, STEM skill development, and conceptual understanding of enzyme function. Findings indicate that students were able to successfully perform the biotechnology procedure under typical classroom constraints while demonstrating meaningful engagement with data literacy, graphing, and experimental reasoning. Hands-on interaction with visible biochemical outcomes appeared to reduce the abstractness of enzyme concepts and support deeper understanding. Importantly, situating the activity within a sustainability context promoted environmental awareness and showed the value of waste-to-value thinking. The study contributes a practical and promising classroom model that bridges biotechnology instruction, integrated STEM practices, and sustainability education. Implications for classroom implementation and future research are discussed.

Keywords: biotechnology education, enzyme learning, integrated STEM education, inquiry-based learning, sustainability education

INTRODUCTION

Integrated STEM education has become a central priority in contemporary science reform efforts aimed at preparing students for the complex scientific, technological, and environmental challenges of the 21st century (Shim & Yoon, 2024). Rather than treating science, technology, engineering, and mathematics as isolated disciplines, integrated STEM emphasizes meaningful connections among domains to promote transferable problem-solving skills and deeper conceptual understanding (Bybee, 2013; Oliveira, et al., 2025; Roehrig et al., 2021; Wekullo, 2026). Current standards such as the next generation science standards (NGSS) further stress the importance of engaging students in authentic scientific and engineering practices, including planning investigations, analyzing data, and constructing evidence-based explanations (National Research Council [NRC], 2013). Within this vision, inquiry-based and hands-on learning environments are widely recognized as critical for

✉ biologyniscbd@gmail.com **(*Correspondence)** ✉ k.zhumagulova@abaiuniversity.edu.kz ✉ Dosmail@inbox.ru
✉ abiltaeva2017@mail.ru ✉ vmasim58@mail.ru

Contribution to the literature

- It provides a classroom-tested model that integrates biotechnology, quantitative reasoning, inquiry-based learning, and sustainability within a single STEM activity using enzyme-assisted processing of carrot pomace.
- It extends enzyme education beyond traditional demonstrations and highly guided laboratory exercises by engaging students in an authentic biotechnology process involving measurement, calculation, graphing, variable identification, and evidence-based reasoning.
- It contributes to sustainability-oriented STEM education by demonstrating how food-waste valorization can serve as a meaningful instructional context for connecting biochemical concepts with environmental awareness and circular-economy thinking, particularly within the underrepresented Kazakhstani educational context.

increasing the kinds of competencies required for modern STEM participation.

Biotechnology education represents a particularly promising context for integrated STEM because it naturally combines biological concepts with quantitative analysis and real-world applications (Usak et al., 2009). Among biotechnology topics, enzyme function is foundational for understanding biochemical processes in living systems and industrial bioprocessing. However, research consistently shows that enzyme concepts remain abstract and challenging for many students, who often struggle to connect molecular-level explanations with observable phenomena (Tibell & Rundgren, 2010). Traditional instruction frequently relies on diagrams or highly structured laboratory exercises, which may lead students to follow procedures without developing mechanistic understanding. As a result, there is growing interest in designing hands-on enzyme investigations that make biochemical processes more visible and cognitively accessible.

At the same time, education for sustainable development (ESD) has called for science learning experiences that connect disciplinary knowledge with environmental responsibility and real-world problem solving (UNESCO, 2017). Food waste has emerged as a powerful educational context because it links everyday experience with global sustainability challenges and circular bioeconomy principles. Waste-to-value approaches, such as recovering useful biomaterials from food processing byproducts, offer authentic opportunities to integrate biotechnology, environmental literacy, and quantitative STEM practices. Despite these converging priorities, relatively few classroom models have embedded enzyme-based biotechnology within sustainability-focused, inquiry-driven STEM instruction.

One scientifically and educationally promising context is the extraction of pectin, a commercially important plant polysaccharide widely used as a gelling and stabilizing agent in the food industry. Agricultural byproducts such as carrot pomace are rich in pectic substances and represent underutilized resources for sustainable bioprocessing. While enzyme-assisted pectin extraction has been well studied in food science, its translation into classroom STEM learning environments remains limited. Most school biotechnology activities continue to rely on simulated or cookbook-style procedures that provide limited opportunities for authentic inquiry, quantitative reasoning, or sustainability integration (Erdogan et al., 2009).

Although integrated STEM education and sustainability-oriented science instruction have gained increasing international attention, their implementation in Kazakhstan is still evolving. Thus, designing and evaluating locally applicable biotechnology learning activities represents an important contribution to STEM education in Kazakhstan. In the Kazakhstani context, STEM-oriented reforms have emphasized inquiry-based learning, competency development, and the practical application of scientific knowledge. However, biotechnology topics such as enzyme function are still often taught through textbook explanations, teacher demonstrations, or highly guided laboratory activities rather than authentic inquiry-based investigations. This creates a local instructional gap: students may learn definitions of enzymes but have limited opportunities to observe enzyme action, collect experimental data, calculate outcomes, and connect biochemical processes with real-world sustainability issues. The present study addresses this gap by introducing a practical classroom activity in Kazakhstan that uses enzyme-assisted pectin extraction from carrot pomace to make enzyme function observable while also engaging students in measurement, graphing, experimental reasoning, and food waste valorization.

The activity also has practical relevance for the Kazakhstani context. Carrots are among the important vegetable crops in Kazakhstan, with reported production of more than 546,000 tons in 2017, indicating the availability of carrot-based agricultural and food-processing residues. Pectin is widely used in the food industry as a gelling, thickening, and stabilizing agent, while carrot pomace is a by-product of carrot juice and vegetable processing that contains valuable fiber and bioactive compounds. Thus, recovering useful materials from carrot pomace can be connected to local food-processing, waste reduction, and circular bioeconomy priorities rather than being viewed only as a classroom exercise.

The purpose of this study is to design and examine an inquiry-based STEM learning activity centered on enzyme-assisted pectin extraction from carrot pomace within a food waste valorization framework.

Research Questions

RQ1. To what extent can students successfully implement an enzyme-assisted pectin extraction process from carrot pomace under typical classroom conditions?

RQ2. What evidence of STEM process skills, including data recording, quantitative calculation, graphing, and experimental reasoning, is demonstrated in students' work during the activity?

RQ3. What levels of conceptual understanding of enzyme function are demonstrated in students' written explanations after the activity?

RQ4. What forms of initial sustainability awareness are evident in students' reflections on food waste valorization?

This study contributes to the literature in three ways. First, it extends integrated STEM education research by presenting a classroom-feasible biotechnology activity that combines enzyme learning, quantitative reasoning, and sustainability education in one instructional model. Second, it contributes to enzyme education by showing how enzyme function can be taught through an authentic waste-to-value process rather than through isolated or highly guided laboratory demonstrations. Third, it adds to sustainability-oriented STEM education by demonstrating how food waste valorization, specifically carrot pomace pectin extraction, can be used as a meaningful context for developing students' STEM process skills, conceptual understanding, and environmental awareness.

LITERATURE REVIEW

STEM Education and the Need for Authentic Inquiry

Research consistently shows that interdisciplinary curricula are particularly effective for developing the competencies required to address complex global problems and workforce demands (Drake & Reid, 2018; Meadows et al., 2024; Roehrig et al., 2021). Within this framework, integrated STEM is commonly defined as instruction that purposefully connects multiple STEM domains through authentic contexts to enhance student learning and application of knowledge (Han et al., 2022).

A central feature of effective STEM education is the use of inquiry-based and hands-on learning approaches. Student-centered pedagogies, such as engineering design challenges, design-based learning, and project-based inquiry, allow learners to actively construct knowledge through investigation, testing, and iteration. These approaches mirror the practices of STEM professionals and promote critical thinking, collaboration, and creativity. The emphasis on inquiry aligns strongly with contemporary standards such as the NGSS, which prioritize scientific and engineering practices and the development of 21st century competencies (NRC, 2013). Such competencies are widely recognized as essential for preparing students to adapt and thrive in a rapidly changing technological society (Stehle & Peters-Burton, 2019).

Importantly, scholars argue that STEM learning becomes most powerful when situated in authentic, real-world contexts. Authentic learning environments connect classroom content to meaningful problems, increasing student motivation, engagement, and the perceived relevance of learning (Roehrig et al., 2021). In integrated STEM frameworks, the use of real-world problems is often considered a defining characteristic because it provides purpose for learning and helps students see the applicability of scientific ideas to everyday life (Drake & Reid, 2018).

Although integrated STEM education has demonstrated considerable potential for improving students' problem-solving abilities, conceptual understanding, and interdisciplinary thinking, its implementation remains challenging. Researchers have reported difficulties such as insufficient teacher preparation, limited instructional time, inadequate laboratory resources, and uncertainty about how to integrate the STEM disciplines in a balanced manner rather than teaching them as parallel subjects (Roehrig et al., 2021). In many classrooms, STEM activities emphasize engagement but provide only superficial disciplinary integration.

Biotechnology and Food Science in School STEM

Biotechnology education has gained increasing attention within STEM curricula as advances in genetics, molecular biology, and bioengineering continue to shape modern society. Educators and policymakers emphasize the importance of introducing biotechnology concepts to promote scientific literacy and prepare students for emerging bioeconomy careers (NRC, 2012). Biotechnology topics such as DNA analysis, fermentation, and genetic engineering are often integrated to connect life science concepts with real-world applications. This growing emphasis reflects a broader movement in STEM education toward interdisciplinary learning that links biology with chemistry, engineering, and technology (Bybee, 2013).

Within this domain, food science contexts have become particularly valuable for STEM instruction because they are familiar, relevant, and inherently interdisciplinary. Food-based investigations, such as fermentation, enzyme activity, and food preservation, provide tangible entry points for understanding complex biochemical processes while increasing student engagement and motivation (McElhatton & McKenna, 2011; Shahali et al., 2017). Laboratory biotechnology experiences in food science can support deeper conceptual learning by allowing students to design experiments, analyze real data, and observe biological transformations firsthand. Research indicates that such authentic laboratory experiences enhance students' inquiry skills, scientific reasoning, and interest in STEM careers when compared with purely theoretical instruction (NRC, 2012).

Despite these benefits, teachers face persistent challenges when implementing biotechnology laboratories in school settings. Common barriers include limited equipment, insufficient teacher preparation, time constraints, and concerns about safety and curriculum alignment (Shahali et al., 2017). As a result, many school biotechnology activities remain highly structured, simulated, or "cookbook-style," where students follow predetermined procedures with limited opportunity for authentic inquiry or problem solving. Moreover, sustainability perspectives, such as food systems thinking, waste reduction, and environmentally responsible bioprocessing, are rarely emphasized in typical classroom biotech labs. This gap suggests a need for more authentic, inquiry-driven biotechnology experiences grounded in sustainable, real-world food science contexts that better reflect contemporary STEM priorities.

Enzyme-Based Learning in Science Education

Recent studies emphasize that inquiry-based enzyme laboratories improve students' conceptual engagement and scientific reasoning (Mack et al., 2023; Şaşmazören & Şahin, 2023). Enzyme concepts occupy a central position in biology and biotechnology education because they explain how biochemical reactions are regulated in living systems. Consequently, many science curricula recommend teaching enzymes through experimental approaches rather than solely through textbook explanations. Inquiry-oriented enzyme investigations, such as examining factors affecting enzyme activity (e.g., temperature, pH, and substrate concentration), help students visualize otherwise invisible molecular processes (Tibell & Rundgren, 2010). Research in science education indicates that when students engage in structured laboratory experiences involving enzymes, they demonstrate improved conceptual understanding and stronger connections between biochemical theory and observable phenomena (Wood, 2009).

Despite their importance, enzymes are widely recognized as a conceptually challenging topic for students. Studies consistently report misconceptions such as viewing enzymes as living organisms, believing enzymes are permanently consumed during reactions, or misunderstanding the role of active sites and specificity (Michael et al., 2002; Tibell & Rundgren, 2010). These misunderstandings often persist because enzyme action occurs at the molecular level and is therefore abstract and difficult to visualize through traditional instruction. When teaching relies heavily on diagrams and lectures, students may memorize terminology without developing mechanistic understanding, leading to fragmented knowledge structures (Koedinger et al., 2012).

Hands-on enzyme investigations have been shown to mitigate these challenges by making enzyme activity observable and meaningful. Classroom activities, such as catalase reactions with hydrogen peroxide, amylase digestion of starch, or fermentation-based enzyme processes, provide concrete experiences that support conceptual change (Wood, 2009). However, prior classroom implementations frequently remain highly guided and verification-oriented, limiting opportunities for authentic inquiry and student-driven reasoning.

Despite the recognized value of inquiry-based enzyme instruction, translating these approaches into everyday classroom practice remains difficult. Enzyme investigations often require specialized materials, laboratory equipment, or teacher expertise that may not be readily available in many schools. Consequently, many laboratory activities become highly structured verification exercises that limit students' opportunities to formulate questions, analyze evidence, and construct scientific explanations.

Sustainability and Food Waste Valorization in STEM

ESD has become a major priority in global education policy, emphasizing the need to equip students with the knowledge, skills, and values required to address environmental and societal challenges. International frameworks stress that STEM education plays a crucial role in advancing sustainability literacy because scientific understanding and technological innovation are central to solving issues such as resource depletion and climate change (NRC, 2012; UNESCO, 2017). Within this perspective, environmental literacy, including systems thinking, responsible decision-making, and awareness of human-environment interactions, is increasingly viewed as an essential outcome of modern science education. Integrating sustainability themes into STEM learning environments is therefore seen as a key pathway for preparing environmentally responsible citizens.

One promising approach within sustainability-oriented STEM is the incorporation of waste-to-value (valorization) concepts, which focus on transforming waste materials into useful products. In the context of food systems, food waste provides an especially powerful and accessible teaching context because it connects chemistry, biology, engineering, and environmental science in a tangible way. Educational researchers note that food-related sustainability topics increase student engagement by linking classroom learning to everyday life and global challenges such as food security and circular economy practices (FAO, 2019; Mak et al., 2020). Activities involving fermentation, enzyme extraction, or bioconversion of food waste can help students understand both biochemical processes and sustainability principles simultaneously, thereby strengthening interdisciplinary STEM learning.

Many existing laboratory activities still prioritize isolated content knowledge rather than systems-level environmental thinking, and few explicitly incorporate waste valorization frameworks. Teachers frequently report constraints related to curriculum time, resources, and lack of ready-to-use instructional models for sustainability-focused biotechnology activities (Erdogan et al., 2012; Mak et al., 2020; O'Neill, 2023).

Although sustainability has become a central objective of contemporary STEM education, researchers have questioned whether sustainability themes are being meaningfully integrated into science instruction. In many cases, environmental topics are introduced only as contextual examples rather than as opportunities for students to engage in authentic scientific inquiry and systems thinking. Teachers also report challenges related to curriculum overload, limited instructional resources, and insufficient professional development for implementing ESD effectively.

Pectin Extraction and Carrot Pomace Research

Pectin is a complex heteropolysaccharide primarily found in plant cell walls, particularly in the middle lamella, where it contributes to structural integrity and cell adhesion. It is widely used in the food industry as a gelling, thickening, and stabilizing agent in products such as jams, jellies, and dairy formulations. Beyond food applications, pectin has growing relevance in pharmaceuticals, biodegradable packaging, and biomedical materials due to its biocompatibility and functional properties (Roman-Benn et al., 2023). Because of its economic value, efficient and sustainable extraction of pectin from plant-based waste streams has become an important research focus (Arumuganainar et al., 2025; Buljeta et al., 2023).

Traditional pectin extraction typically relies on acid hydrolysis under high temperature conditions; however, enzymatic extraction methods have gained attention as greener and more selective alternatives. Enzyme-assisted processes can improve yield, preserve functional quality, and reduce environmental impact by operating under milder conditions (Yapo, 2009). These advances align with broader trends in sustainable bioprocessing and circular bioeconomy practices, where biological catalysts are used to valorize agricultural residues more efficiently.

Carrot pomace, the fibrous byproduct remaining after juice production, represents a promising and underutilized source of pectin. Rich in dietary fiber and pectic substances, carrot processing waste offers an opportunity for waste-to-value conversion within food systems. Recent studies show the feasibility of recovering high-quality pectin from vegetables, supporting both environmental sustainability and industrial resource efficiency (Radić et al., 2024; Subbiah et al., 2025).

Research Gap

Although enzyme-based laboratory activities and sustainability-oriented STEM lessons have been reported in the literature, they typically address these areas separately. Many enzyme education activities focus primarily on illustrating biochemical concepts through short laboratory demonstrations or highly guided verification experiments, with limited emphasis on student inquiry, quantitative reasoning, or real-world applications. Conversely, sustainability-oriented STEM activities often emphasize environmental awareness or engineering design but do not incorporate authentic biotechnology processes that allow students to investigate molecular phenomena through experimentation.

Furthermore, relatively few studies have integrated biotechnology, inquiry-based STEM practices, quantitative data analysis, and ESD within a single classroom activity. Existing instructional models seldom require students to conduct an authentic biotechnology procedure, analyze experimental data through mathematical calculations and graphing, explain enzyme function using scientific evidence, and simultaneously consider the environmental and industrial value of food waste valorization. Consequently, the literature lacks classroom-tested instructional models that bring these elements together in a coherent learning experience, particularly within the Kazakhstani educational context.

METHODS

Research Design

This study employed a classroom-based instructional intervention design to examine the feasibility and educational impact of an enzyme-assisted pectin extraction activity integrated within STEM instruction. The intervention was implemented as an inquiry-oriented laboratory experience embedded in regular coursework. The design allowed simultaneous examination of

(a) procedural feasibility,

(b) student STEM skill engagement, and

(c) conceptual understanding related to enzyme function and sustainability.

The study focused on evaluating the feasibility of implementing the activity and documenting students' learning outcomes within a single classroom implementation. The study followed ethical guidelines for educational research, and participation was voluntary with appropriate permissions obtained.

Participants and Setting

Participants were 24 (14 female and 10 male) university level students enrolled in a STEM-oriented science course at a university in Kazakhstan. The activity was conducted during two regular class periods in a standard laboratory environment. Students worked in small collaborative groups of four to perform the biotechnology procedure. Each group produced one experimental result but each student submitted an individual worksheet. The classroom represented a typical instructional setting with standard time and equipment constraints, allowing evaluation of real-world feasibility.

Instructional Intervention

The instructional activity centered on enzyme-assisted extraction of pectin from carrot pomace within a waste-to-value sustainability framework. The lesson sequence followed an inquiry-based structure:

(1) introduction to enzymes and food waste valorization,

(2) experimental planning and variable identification,

(3) hands-on extraction procedure,

(4) quantitative data collection and graphing, and

(5) evidence-based interpretation and reflection.

Students compared a control condition and an enzyme-treated condition, recorded observations, calculated extraction yields, and constructed graphs to analyze experimental outcomes. The activity was designed to align with engineering practices, particularly planning and carrying out investigations, analyzing and interpreting data, and using mathematics in scientific contexts.

STEM integration was incorporated through the deliberate connection of science, technology, engineering, and mathematics within the activity. The science component focuses on enzyme function, plant cell wall breakdown, and pectin extraction. The technology component involved the use of laboratory tools and procedural techniques for processing carrot pomace, filtration, and measurement. The engineering component was reflected in students' planning of the extraction process, comparison of control and enzyme-treated conditions, identification of variables, and consideration of how food waste could be transformed into a useful product. The mathematics component was embedded through measurement, yield calculation, data organization, graph construction, and interpretation of quantitative results.

Data Sources and Instruments

Multiple data sources were used to capture learning processes and outcomes. Student laboratory worksheets (see **Appendix A**) were collected to examine quantitative reasoning and experimental thinking. Graphical representations produced by students were analyzed to evaluate data literacy practices. In addition, written student reflections and open-ended responses were used to assess conceptual understanding of enzyme function and sustainability connections. All instruments were combined in a single lab worksheet.

Students measured filtrate volume and calculated relative liquid recovery. In this classroom activity, extracted juice volume was used as a practical proxy indicator for pectin release, allowing students to estimate extraction efficiency without specialized analytical equipment. In this classroom activity, the measured liquid volume represented the amount of juice or filtrate recovered after processing and was used only as an indirect instructional indicator of the effect of enzyme treatment on carrot tissue breakdown and liquid release. It did not provide a direct quantitative measurement of isolated pectin.

Data Analysis

Quantitative student outputs (e.g., yield calculations and graphs) were examined descriptively to evaluate successful completion of the biotechnology process and engagement with STEM practices. Qualitative data from students' written explanations and reflections were analyzed using thematic coding. An initial coding framework was developed deductively from the research questions and the relevant literature, focusing on conceptual understanding of enzyme function, STEM process skills, and sustainability awareness. The first author coded all responses iteratively, refining category definitions as coding progressed to ensure consistency in the application of the coding scheme. After the initial coding, the coded responses and category definitions were reviewed by the co-authors, and any ambiguities or disagreements regarding category interpretation were discussed until consensus was reached. Representative student quotations were then selected to illustrate each theme.

RESULTS

Experimental Outcomes of the Classroom Activity

Table 1 and **Table 2** summarize the quantitative outcomes of the classroom enzyme-assisted carrot-processing activity. **Table 1** presents descriptive statistics for relative liquid recovery and completion time, while **Table 2** reports the distribution of classroom

Table 1. Summary of student experimental performance

Measure	M	SD	Minimum	Maximum
Relative liquid recovery (mL/100 g)	3.42	0.88	1.90	5.10
Completion time (min)	41.60	5.20	33.00	52.00

Table 2. Distribution of extraction outcomes

Outcome category	n	Percentage (%)
Successful procedure completion	20	83.30
Partial procedure completion	3	12.50
Unsuccessful procedure completion	1	4.20
Total	24	100

extraction outcomes. In this study, relative liquid recovery refers to the volume of filtrate obtained in relation to the initial mass of carrot pomace. This measure was used as an instructional proxy for enzyme-assisted tissue breakdown and liquid release and should not be interpreted as a direct measure of isolated pectin or pectin extraction efficiency.

In the present classroom implementation, extraction yield refers to the volume of liquid extracted relative to the initial carrot mass, which served as an instructional proxy for pectin release.

The experimental outcomes indicate that students were able to successfully perform the enzyme-assisted pectin extraction under typical classroom conditions. Across the 24 participants, the mean (M) relative liquid recovery was 3.42% (standard deviation [SD] = 0.88), with values ranging from 1.90% to 5.10%. The majority of student groups (83.30%) achieved successful extraction, while a small proportion demonstrated partial (12.50%) or unsuccessful (4.20%) outcomes. The observed variability in yields provided meaningful opportunities for data analysis and interpretation, supporting the activity's alignment with authentic STEM inquiry practices.

Development of STEM Process Skills

Student work products, including data tables, calculations, and graphical representations, were analyzed to evaluate the extent to which the activity supported the development of STEM process skills. Most student groups successfully recorded quantitative measurements for carrot mass and juice volume using appropriate units. Students generally demonstrated careful attention to measurement procedures during the laboratory process. For example, student 11 wrote in the lab sheet, "We measured the carrot pulp to be exactly 100 g before starting the extraction." Similarly, student 2 noted, "We repeated the volume reading to make sure the measurement was correct." However, minor issues were observed in a small number of submissions. Some students omitted units or rounded values inconsistently. For instance, student 17 recorded juice volume without specifying milliliters, while student 14 reported slightly inconsistent mass values between trials. Despite these minor errors, the overall quality of data recording was satisfactory for the grade level.

Analysis of student calculations indicated that many students correctly applied the percent yield formula. Many students showed their work clearly and demonstrated appropriate mathematical reasoning. Student 15 explained, "I divided the juice volume by the original mass and multiplied by 100 to get the percent yield." Student 6 similarly wrote, "The enzyme sample had a higher percent yield because the calculated value was larger than the control." These responses indicate that students were able to connect the mathematical procedure with the experimental purpose.

A smaller group of students demonstrated arithmetic mistakes or formula misplacement. For example, student 21 reversed the numerator and denominator, resulting in an incorrect percentage. Student 8 completed the calculation correctly but did not show intermediate steps. These patterns show that while conceptual understanding was generally strong, some students would benefit from additional scaffolding in quantitative communication.

Most students constructed bar graphs that appropriately compared the control and enzyme-treated conditions. The majority included correctly labeled axes and descriptive titles. Students generally interpreted the graphical patterns accurately. Student 9 wrote, "The bar graph shows the enzyme group is higher, which means the enzyme-treated condition produced greater filtrate recovery". Similarly, student 20 noted, "From the graph, we can clearly see the treated sample produced more juice." Common minor issues included uneven bar spacing, missing units on axes, or inconsistent scaling. Despite these formatting issues, the graphical representations were typically interpretable and supported students' evidence-based reasoning.

Students were also asked to identify the independent and dependent variables. Most students correctly identified enzyme treatment as the independent variable and juice yield as the dependent variable. This indicates that the activity supported foundational experimental design reasoning. A small number of students confused controlled variables with the independent variable, showing an area for future instructional reinforcement.

As shown in **Table 3**, a large majority of students demonstrated proficiency in core STEM process skills, particularly in data recording (83.00%) and graphical representation (79.00%).

Conceptual Understanding of Enzyme Function

Analysis of students' written explanations in the claim-evidence-reasoning section indicated substantial progress in linking enzyme action to plant cell wall breakdown and increased extraction efficiency. Students' responses were coded for three levels of understanding:

Table 3. Student demonstration of STEM process skills

Skill area	Indicator	n	Percentage (%)
Data recording	Recorded mass and volume with correct units	20	83.00
	Minor unit omissions or inconsistencies	4	17.00
Yield calculation	Correct formula and computation	18	75.00
	Arithmetic or formula errors	6	25.00
Graph construction	Correct bar graph with labeled axes	19	79.00
	Graph present but with formatting issues	5	21.00
Experimental reasoning	Correctly identified independent and dependent variables	18	75.00
	Variable confusion	6	25.00

Note. Percentages are rounded to the nearest whole number

Table 4. Levels of student conceptual understanding of enzyme function

Understanding level	Description	n	Percentage (%)
Mechanistic understanding	Explicit connection between enzyme action and cell wall/pectin breakdown	7	29.00
Functional but partial understanding	Correct general idea (enzymes break down material) without molecular detail	12	50.00
Descriptive or emerging understanding	Observation-based with limited causal explanation	5	21.00

Note. Percentages are rounded to the nearest whole number

(a) mechanistic understanding,

(b) functional but partial understanding, and

(c) descriptive understanding.

A subset of students demonstrated clear mechanistic reasoning by explicitly connecting enzyme activity to the breakdown of structural components in carrot tissue. These students used appropriate scientific language and causal explanations. For example, student 4 wrote, “The enzyme increased the juice yield because it broke down the pectin and cell wall materials, which released more liquid from the carrot pulp.” Similarly, student 12 explained, “Enzymes act as catalysts that weaken the plant cell walls, so more juice can escape during filtration.” Student 16 stated, “When the enzyme was added, it degraded the structural polysaccharides in the carrot, which explains the higher yield we measured.” In another response, student 24 noted, “The enzyme treatment worked because it chemically broke apart components of the cell wall, especially pectin, making extraction easier.”

Many students demonstrated correct but less detailed explanations. These responses typically identified that enzymes “break down” material but did not always specify the cellular or molecular target. For instance, student 18 wrote, “The enzyme helped break down the carrot so more juice came out.” Student 23 explained, “Adding enzyme made the pulp softer and easier to filter, which increased the yield.” Student 7 stated, “The enzyme speeds up the breakdown process in the carrot, so we got more liquid.” Similarly, student 8 noted, “Because enzymes help reactions happen faster, the carrot released more juice.”

A smaller group of students provided primarily observational descriptions with limited causal explanation. These students correctly reported the outcome but showed incomplete mechanistic reasoning. Student 2 wrote, “The enzyme group had more juice than the control.” Student 22 stated, “The treated sample worked better, but I am not completely sure why the enzyme caused it.”

As summarized in **Table 4**, most students demonstrated at least functional understanding of enzyme action, with 29.00% reaching a mechanistic level of explanation.

Initial Sustainability Awareness and Food Waste Utilization

Students’ written reflections and exit responses were analyzed to examine the extent to which the activity supported awareness of sustainability and food waste valorization. Students demonstrated increased recognition that carrot pomace, typically considered waste, can be repurposed into useful bioproducts such as pectin.

Many students explicitly connected the laboratory activity to broader environmental themes. Their responses indicated that the hands-on experience helped them reconsider the value of food-processing by-products. For example, student 1 wrote, “I learned that the leftover carrot pulp is not just waste and can be used to make useful materials.” Similarly, student 14 noted, “This experiment showed that food waste can be recycled into something valuable instead of being thrown away.” Student 20 explained, “Using carrot pomace for pectin helps reduce waste in the food industry.” Student 24 commented, “I did not know vegetable waste could be reused in biotechnology.”

Several students extended their thinking to environmental benefits such as waste reduction and resource efficiency. Their reflections indicated

Table 5. Students' initial sustainability awareness of food waste utilization

Awareness level	Description	n	Percentage (%)
Explicit sustainability connection	Clearly links activity to waste reduction or environmental benefit	11	46.00
General awareness	Mentions reuse or recycling with limited elaboration	8	33.00
Surface-level awareness	Vague or minimal environmental connection	5	21.00

Note. Percentages are rounded to the nearest whole number

developing systems-level awareness. Student 14 stated, "If companies reuse carrot waste, it could reduce the amount of trash going to landfills." Student 5 wrote, "This process supports sustainability because it uses materials that would normally be discarded." Student 16 observed, "Biotechnology can help solve environmental problems by turning waste into useful products." Similarly, student 7 noted, "This lab showed how science can help protect the environment by reducing food waste."

A smaller group of students made only general or surface-level references to sustainability. While these students recognized that the activity involved reuse, their explanations lacked depth. For instance, student 18 wrote, "The experiment helps the environment." Student 9 stated, "It is good because it uses leftovers." Student 10 commented, "This activity is related to recycling."

Although brief, these responses still indicate initial awareness and provide opportunities for deeper future instruction.

Table 5 indicates that nearly half of the students (46.00%) made explicit connections between the activity and environmental sustainability.

DISCUSSION

The results demonstrate that students were able to successfully carry out a simplified enzyme-assisted biotechnology process within typical classroom conditions, showing the practical feasibility of the activity. Importantly, the procedure maintained key elements of authentic scientific practice, such as experimental setup, comparison of experimental and control conditions, and observation of biochemical outcomes, rather than reducing the experience to a purely demonstrative task. This finding is significant because prior research has noted that many biotechnology activities are constrained by equipment limitations, time pressures, and teacher preparedness, often leading to highly structured or simulated experiences (Shahali et al., 2017). By contrast, the present implementation shows that meaningful, inquiry-oriented biotechnology work can be conducted within real classroom constraints while preserving disciplinary authenticity. From a STEM learning perspective, the feasibility of this approach strengthens its classroom value, suggesting that well-designed enzyme-based investigations can overcome common implementation barriers and provide students with more realistic exposure to contemporary biotechnological practices.

Beyond procedural success, the activity appears to have supported meaningful development of core STEM practices by positioning students as active investigators rather than passive followers of laboratory steps. The requirement to record measurements, organize results, and construct graphs engaged students in data literacy and quantitative reasoning processes that mirror authentic scientific work. These practices are central to the NGSS, which emphasize analyzing and interpreting data, using mathematics and computational thinking, and planning and carrying out investigations as essential dimensions of science learning (NRC, 2013).

The observed skill development can be explained through principles from inquiry-based learning and integrated STEM frameworks. This finding aligns with prior inquiry-based enzyme curricula demonstrating improved student engagement in authentic biochemical investigations (Spence et al., 2020). Inquiry environments support deeper learning when students must generate evidence, interpret patterns, and justify conclusions rather than simply verify known results. In this activity, graphing enzyme-related outcomes and comparing conditions required students to engage in experimental thinking, considering cause-effect relationships, recognizing sources of error, and reasoning from data. Integrated STEM models similarly argue that meaningful learning occurs when disciplinary knowledge is mobilized through authentic problem solving that blends science concepts with mathematical tools (Roehrig et al., 2021).

The improvement in students' conceptual understanding can be interpreted through constructivist and experiential learning perspectives, which emphasize that learners build robust knowledge structures through active engagement with phenomena. Enzyme function is inherently abstract because it occurs at the molecular level; however, the hands-on extraction process provided observable macroscopic evidence of biochemical change. By comparing enzyme-treated and control samples and observing extraction outcomes, students were able to anchor symbolic and microscopic ideas to tangible experiences. From a constructivist standpoint, this likely supported the restructuring of prior conceptions, as students were not merely told how enzymes work but experienced cause-effect relationships through their own investigations (NRC, 2012).

Although the activity supported sustainability awareness for many students, 21.00% demonstrated only surface-level understanding. This may be explained by the short duration of the intervention, students' limited prior exposure to sustainability concepts, and the stronger emphasis placed on the biochemical and procedural aspects of the activity. Some students may have recognized that carrot pomace could be reused but did not yet develop deeper systems-level reasoning about waste reduction, resource efficiency, or circular economy practices.

One of the most significant contributions of this study lies in its explicit integration of sustainability within an authentic biotechnology learning experience. By framing enzyme-assisted pectin extraction as a food waste valorization process, the activity moved beyond traditional laboratory goals toward environmental problem solving. Students were learning biochemical principles and also engaging with the concept that organic waste streams can be transformed into valuable products. This positioning aligns closely with ESD, which calls for learning experiences that connect scientific knowledge with responsible resource use and circular economy thinking (UNESCO, 2017).

Importantly, the design demonstrates how STEM and sustainability can be meaningfully integrated rather than superficially appended. The carrot pomace context provided real-world relevance that required students to apply biotechnology knowledge, quantitative reasoning, and systems thinking simultaneously. Such integration is emphasized in contemporary STEM frameworks, which argue that complex socio-scientific problems are particularly effective for fostering interdisciplinary competence and student motivation (NRC, 2012).

The outcomes of this study align with prior enzyme-teaching research showing that students learn enzyme function more effectively when instruction is grounded in experimentation rather than purely symbolic or lecture-based approaches. Classroom and outreach enzyme labs commonly use observable reactions (e.g., digestion or catalase-type activities) to make molecular processes "visible," supporting conceptual change and reducing common misunderstandings (Mack et al., 2023; Tibell & Rundgren, 2010). In this sense, the present activity is consistent with the broader inquiry-learning literature and NGSS-aligned priorities that emphasize planning investigations, analyzing data, and building explanations from evidence (NRC, 2012, 2013). Where this work adds credibility is that these learning benefits emerged through a biotechnology process that preserved authentic features of scientific work (variable testing, evidence-based reasoning) rather than functioning as a short demonstration.

At the same time, the findings extend biotechnology lab education research that repeatedly documents implementation barriers in schools, limited equipment, time, and teacher confidence, often resulting in simulated or highly scripted experiences (Aydın et al., 2023; Steele & Aubusson, 2004). The feasibility demonstrated here suggests that meaningful biotechnology can be enacted under classroom constraints while still supporting inquiry and quantitative reasoning. This complements emerging efforts to broaden access to biotechnology learning (including more modern delivery models) while maintaining authentic engagement with biological processes (Vera-Choqqueccota et al., 2025). It also resonates with food science education work showing that familiar food contexts (e.g., fermentation) can support interdisciplinary, curiosity-driven inquiry and sustained engagement (Sørensen, 2023).

Integrated STEM reviews emphasize that strong models connect disciplines through real-world problems and inquiry, yet they also note that classroom-ready examples remain uneven and often lack coherent integration beyond surface-level context (Portillo-Blanco et al., 2024). By centering enzyme-assisted extraction within a food waste valorization context, this study extends typical enzyme labs (often decontextualized) and typical biotech labs (often simulated) into a more authentic, sustainability-forward model that reflects current ESD priorities and better operationalizes integrated STEM in practice (NRC, 2012; UNESCO, 2017).

CONCLUSIONS, IMPLICATIONS, LIMITATIONS, AND FUTURE RESEARCH

This study shows that enzyme-assisted pectin extraction from carrot pomace can function as an effective, classroom-feasible model for integrated STEM learning. The activity successfully engaged students in authentic biotechnology practices while supporting the development of quantitative reasoning, data literacy, and experimental thinking aligned with contemporary STEM frameworks. By making enzyme action observable through hands-on investigation, the approach helped reduce the abstractness that often characterizes molecular biology instruction and promoted conceptual understanding. These findings reinforce the value of inquiry-oriented laboratory experiences that situate core scientific ideas within meaningful, evidence-generating tasks.

Importantly, the work contributes a novel sustainability dimension by embedding food waste valorization within biotechnology instruction. This integration advances ESD goals by connecting biochemical knowledge with environmental responsibility and circular economy thinking. The results show that well-designed waste-to-value investigations can simultaneously strengthen disciplinary learning and environmental literacy while remaining practical for typical classroom settings.

The findings of this study show several practical implications for classroom implementation. First, the activity demonstrated feasibility within typical constraints, indicating that meaningful biotechnology experiences do not necessarily require advanced laboratory infrastructure.

Second, the accessibility of materials and the modular structure of the procedure support flexibility in instructional planning. Teachers can scale the activity based on available time, student level, and curricular goals, for example, emphasizing basic enzyme concepts in introductory courses or extending the quantitative analysis component in more advanced STEM classes. Because the investigation naturally incorporates measurement, graphing, and variable testing, it can reinforce NGSS science and engineering practices while also supporting mathematics integration. Third, findings also show that students need stronger scaffolding when completing the quantitative and graphical components of the activity. Although most students successfully recorded data, calculated yield, and constructed graphs, some procedural errors were observed, including missing units, inconsistent rounding, incorrect formula use, and graph-formatting problems.

Several limitations should be acknowledged when interpreting the findings of this study. First, the implementation was conducted within a single classroom context with a relatively limited number of participants, which may constrain the generalizability of the results to other grade levels, settings, or demographic populations. Second, the intervention was of relatively short duration, capturing students' immediate engagement and understanding but not allowing examination of longer-term retention, transfer of learning, or sustained impacts on STEM interest. Third, students' conceptual understanding and sustainability awareness were examined mainly through laboratory worksheets, written explanations, graphs, and reflections; they may have been influenced by students' desire to provide expected or teacher-approved responses. Fourth, the study did not use objective pre- and post-tests to measure changes in students' enzyme understanding before and after the intervention. Fourth, the quantitative findings were based primarily on descriptive statistics, while students' conceptual understanding and sustainability awareness were examined through thematic interpretation of worksheets and written reflections. Thus, the results should not be interpreted as evidence of measurable learning improvement or causal instructional effectiveness.

Future investigations could incorporate more sophisticated molecular or analytical measures, such as quantitative yield comparisons or basic spectrophotometric analysis, to explore how increasing biochemical rigor influences both learning outcomes and classroom feasibility. Moreover, adding group discussions or case studies on the "circular economy" would help students move from surface-level awareness toward a more comprehensive understanding of sustainability and circular economy principles.

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Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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APPENDIX A: STUDENT WORKSHEET

STEM Lab: Extracting Pectin From Carrots

Name: ____________________
Date: ____________________
Class: ____________________

Part 1 — Pre-lab questions

1. What is pectin?
   ____
2. Where is pectin commonly used in food?
   ____
3. What do enzymes do in biological systems?
   ____
4. Write the investigation question: How does _________________________ liquid recovery from carrot pomace?
   ____

Part 2 — Hypothesis

If enzyme is added to carrot pulp, then ____.
Because ____.

Part 3 — Experimental data

Materials used (check):

☐ Carrots
☐ Blender
☐ Warm water
☐ Enzyme
☐ Filter paper
☐ Beaker/jar

Table A1. Raw data table

Group	Mass of carrot pulp (g)	Juice volume (mL)	Observations
Control			
Enzyme			

Part 4 — Calculations

Formula: Yield (%) $= \frac{\text{Juice volume}}{\text{Initial pulp mass}} \times 100$.

Control relative liquid recovery:

Show work: ____.

Answer: __________ %

Enzyme yield:

Show work: ____.

Answer: __________ %

Part 5 — Graph

Create a **bar graph** comparing:

- Control relative liquid recovery
- Enzyme-treated relative liquid recovery

Title: ____

Part 6 — Analysis questions

1. Which sample produced more juice?

   ____

2. Why did the enzyme change the result?

   ____

3. What variable was the independent variable?

   ____

4. What was the dependent variable

   ____

5. Identify one possible source of error.

   ____

Part 7 — STEM & sustainability

The research shows carrot pomace can be reused instead of wasted.

Explain ONE environmental benefit of reusing carrot pomace instead of discarding it: ____________________

____

Real-world application of pectin: ____

____

Part 8 — Claim-evidence-reasoning

Claim: ____

Evidence (data): ____

Reasoning (science explanation): _______________________________________

Exit reflection:

Circle one:

- I understand how enzyme treatment affects carrot tissue and liquid recovery.
- I somewhat understand.
- I am still confused.

One thing I learned today: ____