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Project-Based Learning on Phenols in Senior High School Organic Chemistry: Unveiling Chemical Wonders in Chu-Style Lacquerware

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Abstract*— *This study employs the national intangible cultural heritage "Chu-style Lacquerware Decoration Techniques" as an authentic context, with "urushiol"—its core film-forming substance—as the knowledge and inquiry thread. Through completing five sub-tasks—"Initial Exploration of Lacquerware," "Unveiling the Secrets of Urushiol," "Scientific Improvement," "Innovative Application," and "Achievement Exhibition"—students deeply construct knowledge systems encompassing the structure, acidity, color reaction, oxidation properties of phenolic hydroxyl groups, and the characteristics of phenolic derivatives. The project integrates literature research, experimental inquiry, scheme design, and traditional cultural inheritance, fostering students' abilities in evidence-based reasoning, scientific inquiry, and innovation awareness. Students profoundly appreciate the value of chemistry in cultural heritage protection and innovation, achieving the unified development of "knowledge, emotion, will, and action" core competencies.

I. ANALYSIS OF PROJECT THEME AND CONTENT

The core teaching content of this project corresponds to "Theme 2: Properties and Applications of Hydrocarbons and Their Derivatives" under "Module 3: Fundamentals of Organic Chemistry" in the elective compulsory curriculum of the General Senior High School Chemistry Curriculum Standards (2017 Edition, Revised 2020). The latest version of the standards requires: "to recognize the composition, structural characteristics, properties, transformation relationships of phenols and their important applications in production and daily life"; "to understand the relationship between organic reaction types and the composition and structural characteristics of organic compounds"; and "to understand, in combination with practical production and living contexts, the potential environmental and health impacts of certain hydrocarbons and their derivatives, to appreciate the significance of 'green chemistry' principles in organic synthesis, and to pay attention to the safe use of organic compounds".

In the People's Education Press elective compulsory textbook (Book 3), phenol serves as the representative compound of the phenol class, with emphasis on its weak acidity, substitution reactions, and color reactions.

However, studying phenol as a single substance appears somewhat limited. Urushiol in raw lacquer is a highly distinctive natural catechol derivative widely applied in Chu culture lacquerware. Its structure features two phenolic hydroxyl groups and an unsaturated long-chain hydrocarbon group containing 15-17 carbon atoms. This structure determines that it possesses both general properties of phenols (weak acidity, color reaction with $FeCl_3$) and unique characteristics (oxidative polymerization catalyzed by laccase under specific temperature and humidity conditions). This authentic, complex, and culturally rich carrier provides students with a depth and breadth of phenol knowledge far exceeding that of textbook materials.

Through the exploration of Chu-style lacquerware, students in this project will not only master the core knowledge of phenols but also establish the chemical concept that "structure determines properties, and properties determine applications and craftsmanship," understand the scientific principle that "chemical reactions can be regulated by controlling reaction conditions" (such as the regulation of humidity and temperature in the traditional "yin drying" [shaded air-drying] process), and profoundly appreciate the important role of chemistry in protecting and inheriting excellent traditional Chinese culture.

II. PROJECT TEACHING OBJECTIVES

(1) Through analyzing the cross-sectional structures of lacquer films from Warring States Chu tombs (such as the "wood base-primer layer-red lacquer film layer-pattern layer" structure of the inner coffin from the Xinzhuang Chu Tomb in Pingdingshan, Henan) and compositional data, students will identify the main organic component of lacquer films as raw lacquer (urushiol) and inorganic pigments as cinnabar (HgS), pararealgar (As_4S_4), among others. Students will be able to predict the properties of urushiol from its molecular structure (catechol derivative with long-chain hydrocarbon groups), explain its weak acidity, color characteristics, and oxidative polymerization capability, thereby cultivating their competence in "macroscopic identification and microscopic analysis."

(2) Through designing and implementing comparative experiments (such as acidity and color reaction comparisons between urushiol and phenol; curing experiments of urushiol under different humidity conditions with and without laccase), students will obtain evidence, inductively reason the properties of phenolic hydroxyl groups and the conditions for urushiol polymerization, and construct a phenol cognition model based on "structure-properties-conditions-applications," thereby cultivating their competence in "evidence-based reasoning and model cognition."

(3) Based on the pain points of traditional raw lacquer craftsmanship (allergenicity, slow drying), students will be able to consult literature, propose scientific hypotheses for reducing allergenicity or improving workability, design preliminary improvement experimental schemes (such as urushiol-epoxy resin blending), and conduct simple performance tests, thereby experiencing the technological innovation process and cultivating their scientific practical abilities in scientific explanation and discovery, creation and application.

(4) Through understanding the glorious history and modern dilemmas of Chu-style lacquerware, students will appreciate the chemical wisdom and cultural spirit of ancient craftsmen, enhancing their national pride and cultural confidence. Through discussing the application of chemistry in lacquer art protection and innovation, students will deeply understand the dual impact of chemical technology on social development, form concepts of sustainable development and sense of responsibility , and cultivate their scientific attitude toward chemistry and awareness of actively assuming social responsibility.

III. PROJECT TASKS AND TEACHING PROCESS

The specific tasks and process design of this project are shown in Table 1:

Table 1 Teaching Process

Project Task	Student Activities	Teacher Support	Design Intent
Task Introduction: Initial Exploration of Lacquerware	1. Appreciate the beauty of Chu-style lacquerware. 2. Observe cross-sectional diagrams of Warring States lacquerware, analyzing its layered structure and possible components. 3. Propose the core question: "Why can 'lacquer black' remain incorruptible for millennia?"	1. Prepare videos, high-definition cultural relic images, lacquer film cross-section micrographs, and compositional data tables. 2. Guide students to extract scientific questions from cultural relic phenomena: "What is the core organic component?"	Create an authentic intangible cultural heritage context to stimulate interest and national pride, drive project initiation, and naturally introduce the core substance—urushiol.
Task 1: Unveiling the Secrets of Urushiol	1. Model building: Compare phenol and catechol models, construct urushiol molecular models, and predict similarities and differences in properties. 2. Experimental inquiry: weak acidity; color reaction; oxidative polymerization.	1. Provide molecular model kits and safe experimental materials. 2. Design experimental instruction manuals, guiding control of variables. 3. Explain laccase catalysis and oxygen free radical polymerization mechanisms.	Through models and experiments, construct core knowledge, deeply understand phenol properties, and explore the unique curing characteristics of urushiol, deciphering the scientific principles of the "yin drying" process.
Task 2: Scientific Improvement	1. Problem identification: Analyze disadvantages of traditional raw lacquer. 2. Literature research: Consult modern urushiol modification patents/literature. 3. Scheme design: Design improvement schemes in groups. 4. Experimental verification: Prepare blended samples and test curing speed and acid-base resistance.	1. Provide information on raw lacquer disadvantages and modern modification cases. 2. Guide scheme design and safe operation. 3. Provide simple performance testing methods.	Apply chemical knowledge to solve real problems, cultivating engineering thinking, green chemistry concepts, and innovative practical abilities.
Task 3: Innovative Application	1. Modern application research. 2. Design activity: Design a concept drawing/model of a cultural and creative product incorporating lacquer art	1. Showcase modern urushiol resin application cases. 2. Organize design workshops and provide design tools.	Connect past and present, appreciate the modern transformation of traditional chemical wisdom, and cultivate interdisciplinary innovation and expression

		elements.		abilities.
Task 4: Exhibition	Achievement	1. Group presentation: Display the entire project's research results. 2. Hold a small exhibition: "Chemical Codes in Chu Lacquer" popular science exhibition. 3. Interactive evaluation: Conduct peer evaluation among groups based on evaluation rubrics	1. Develop detailed achievement presentation evaluation rubrics. 2. Organize exhibitions and presentation sessions, inviting art or history teachers to participate in evaluation. 3. Guide students in project reflection.	Integrate knowledge, abilities, comprehensive display and evaluation, and competency outcomes; exercise expression, communication, and reflection abilities; solidify learning outcomes and enhance cultural confidence.

IV. PROJECT IMPLEMENTATION PROCESS AND STUDENT LEARNING OUTCOMES

(1) Task Introduction: Initial Exploration of Lacquerware—Deciphering the Mystery of Millennial Preservation

[Teacher] Plays video materials of cultural relics including lacquerware from the Tomb of Marquis Yi of Zeng, the Tiger-Seat Bird-Frame Drum, and the painted lacquer bamboo box from the Baoshan Chu Tomb.

[Students] Watch the videos, marveling at the brilliant colors and exquisite patterns of the lacquerware.

[Teacher] These exquisite artifacts originate from Warring States Chu tombs over two thousand years ago. A crucial question is: why have their organic coatings remained incorruptible after millennia?

[Students] Perhaps they used very stable materials that are not easily degraded.

[Teacher] Displays the micrographic cross-section of the lacquer film from the inner coffin of Tomb No. 1 at the Xinzhuang Chu Tomb site in Pingdingshan, Henan (clearly showing the wood base, black primer layer, red lacquer film layer, and pattern layer) and the EDS compositional analysis data table (showing that the red layer contains C, O, S, and Hg).

[Teacher] Observing the cross-section, how many layers does the lacquer film have? What does the compositional data indicate the red pigment is? What might the main organic component be?

[Students] There are four layers. The red pigment is cinnabar (HgS). The organic component... literature says it is raw lacquer.

[Teacher] Exactly! Raw lacquer, this natural resin collected from lacquer trees, is precisely the "core technology" behind the millennial preservation of Chu lacquerware. And the most important functional component in raw lacquer, accounting for 50%-80%, is a substance called urushiol. It belongs to the phenolic compounds we are studying in this chapter. Today, we will transform into "science detectives" and "craft improvement engineers" to together Explore the Chemical Miracles in Chu-style Lacquerware.

(2) Task 1: Unveiling the Secrets of Urushiol—Exploring Phenolic Characteristics and Film-Forming Mechanisms

Phase 1: From Macroscopic to Microscopic—Predicting Properties from Molecular Structure

[Teacher] Urushiol is a phenolic compound. What similarities and differences does it have with phenol we just studied? Please make bold predictions based on its name and applications.

[Students] Both have phenolic hydroxyl groups, so they probably have acidity and can undergo color reactions. But since it can cure to form a hard film, it may have other special properties or structures.

[Teacher] Excellent! Let's reveal its true nature. Urushiol, more precisely, is a mixture of various catechol derivatives, with side chains being unsaturated long chains containing 15-17 carbons.

[Students] Work in groups to construct molecular models of urushiol (represented by a typical structure) and phenol.

[Teacher] Comparing the models, what structural differences can you identify? How might these differences lead to different properties?

[Students] Urushiol has two phenolic hydroxyl groups (in ortho positions), while phenol has only one; urushiol has a very long tail (side chain). The two phenolic hydroxyl groups may make it more acidic or more reductive; the long tail may make it more greasy, less volatile, and possibly participate in cross-linking.

Phase 2: Experimental Inquiry—Verifying Properties and Exploring Film Formation

Sub-activity 1: General Properties of Phenols—Weak Acidity and Color Reaction

[Students] (In a fume hood, using low-allergenicity modified urushiol samples)

① Acidity verification: Take two test tubes, add small amounts of phenol and modified urushiol respectively, dropwise add NaOH solution, observe the phenomena; then add dilute hydrochloric acid.

② Color reaction: Take another two test tubes, add small amounts of phenol and modified urushiol solutions respectively, add 1-2 drops of $FeCl_3$ solution, observe and record the colors.

[Experimental Records and Conclusions] Experimental results are shown in Table 2:

Table 2 Experimental Phenomena and Conclusions of "General Properties of Phenols"

Experiment	Phenol	Modified Urushiol	Conclusion
Add NaOH	Dissolves, forming sodium phenoxide	Dissolves, forming sodium urushiolate	Both have weak acidity and can react with bases
Then add HCl	Phenol re-precipitates	Urushiol re-precipitates	/
Add $FeCl_3$	Solution turns purple	Solution turns blue-purple	Both can undergo color reactions with $FeCl_3$; color differences stem from structural differences

Sub-activity 2: Unique Characteristics of Urushiol—Oxidative Polymerization (Controlled Variable Inquiry)

[Teacher] The most magical property of urushiol is its ability to cure in air to form a hard, durable lacquer film. Ancient craftsmen controlled the environment through "yin rooms" (shaded drying chambers) to dry lacquerware. What is the secret behind this?

[Students] Perhaps it requires specific temperature? Humidity? Or maybe a catalyst?

[Teacher] Scientific inquiry requires designing experiments to verify hypotheses. It is known that raw lacquer contains a key enzyme—laccase—which can catalyze oxidation reactions. Please design a set of controlled experiments to investigate the effects of laccase and humidity on urushiol curing.

[Students] Finalized experimental scheme:

Group A: Urushiol + Laccase → placed in high-humidity environment (humidity >80%)

Group B: Urushiol + Laccase → placed in dry environment (humidity <30%)

Group C: Urushiol (without laccase) → placed in high-humidity environment (humidity >80%)

[Students] Set up the three group conditions, observe and record state changes of samples at different time intervals (fluidity, viscosity, surface curing status).

[Experimental Phenomena and Conclusions] Experimental results are shown in Table 3:

Table 3 Experimental Phenomena and Conclusions of "Unique Characteristics of Urushiol"

Group	Conditions	Phenomena (after 24 hours)	Conclusion
Group A	Laccase + High humidity	Surface basically cured, lacquer film formed	Laccase and high humidity are key conditions for rapid urushiol curing. Laccase catalyzes the oxidation of urushiol to form quinone intermediates under appropriate temperature, which then undergo free radical polymerization and cross-linking to form a network polymer film.
Group B	Laccase + Dry	Still viscous liquid, not cured	/
Group C	No laccase + High humidity	Color deepened, slightly thickened, but not cured	/

[Teacher] Through the above inquiry, we have not only verified the general properties of urushiol as a phenol but also revealed its unique oxidative polymerization characteristics and the scientific connection to the core craft of Chu-style lacquerware—"yin drying" (shaded air-drying). This is the magic of chemistry: interpreting millennia of wisdom at the molecular level.

(3) Task 2: Scientific Improvement—Optimizing Traditional Lacquer Art

[Teacher] Although traditional raw lacquer has excellent properties, it has two major pain points: first, urushiol can cause allergic contact dermatitis; second, drying heavily relies on the "yin room" environment, resulting in low efficiency. How can we use chemical knowledge to improve it?

[Students] Consult information cards and propose improvement ideas.

Group 1 Idea: Hydrogenate the double bonds on the side chain to reduce its binding capacity with skin proteins, thereby decreasing allergenicity.

Group 2 Idea: Blend raw lacquer with epoxy resin. Epoxy resin can provide a rigid skeleton, potentially accelerating the overall curing speed and improving workability.

[Teacher] Idea 1 involves organic synthesis, which is difficult to achieve at the secondary school level. Idea 2, blending modification, is more practical for experimental verification. Please Group 2 design a simple blending modification experimental scheme.

[Students] Take two equal portions of modified urushiol, one as control, the other mixed with a certain proportion of epoxy resin and curing agent. Apply both simultaneously onto glass slides, place them in the same environment, and observe and record the tack-free time and through-dry time. Additionally, dilute NaOH solution can be dropped onto the surface for preliminary comparison of alkali resistance.

[Students] Conduct the experiment and record data.

[Experimental Results] The experimental group (urushiol-epoxy blend) showed significantly shorter tack-free time compared to the control group, and the formed lacquer film demonstrated improved alkali resistance.

[Teacher-Student Reflection] Blending improved performance, but may have sacrificed the purely natural characteristics. Chemical improvement requires seeking balance among performance, cost, environmental protection, and tradition.

(4) Task 3: Innovative Application

Modern Application Research: Through materials provided by the teacher, students learned that urushiol and its modified products (urushiol-acetal resins, urushiol-epoxy coatings) are widely applied in ships, petrochemical industries, underground engineering, high-end furniture, and other fields due to their excellent corrosion resistance and wear resistance.

Creative Design: Each group completed the design task "When Lacquer Art Meets Modern Life," producing works including: conceptual phone cases made from modified urushiol materials, LED lampshades with Chu decorative patterns, and lacquer art jewelry design drawings or models.

(5) Task 4: Achievement Exhibition

Each group conducted final presentations, comprehensively displaying the project research process and achievements, and held a small exhibition. Teachers and students conducted peer and teacher evaluations based on assessment rubrics (covering multiple dimensions including knowledge application, inquiry depth, innovation, collaboration, and expression).

V. PROJECT TEACHING REFLECTION AND IMPROVEMENT SUGGESTIONS

(1) Project Effectiveness:

This project successfully achieved deep integration of intangible cultural heritage with core high school chemistry knowledge. Students were no longer passive learners of "phenol" properties; instead, they actively constructed knowledge and understood concepts while solving authentic problems such as "why can lacquerware remain incorruptible for millennia" and "how to improve traditional lacquer art." They also enhanced higher-order thinking abilities including experimental inquiry, evidence-based reasoning, and innovative application, achieving synchronous development in cultural identity and core competencies.

(2) Implementation Challenges and Solutions:

The strong allergenicity of urushiol poses the greatest safety challenge. Solutions include: ① using low-allergenicity alternatives such as hydrogenated modified urushiol for hands-on operations; ② completing core oxidative polymerization experiments using virtual simulation software; ③ for operations that must be conducted, strictly equipping with protective gloves and goggles and performing in fume hoods. The issue of tight class hours can be addressed by moving some literature review and scheme design phases to pre-class preparation, and extending some production activities to after-school clubs.

(3) Improvement Suggestions:

Inviting lacquerware intangible cultural heritage inheritors or relevant enterprise engineers to conduct lectures or workshops on campus would deepen industry-university-research connections and significantly enhance the project's appeal; more precise evaluation tools could be introduced, such as the SOLO (Structure of the Observed Learning Outcome) taxonomy, to conduct more accurate assessments of students' thinking levels in organic synthesis route design and problem-solving; students could be guided to further explore the chemical properties of inorganic pigments in lacquerware (cinnabar, pararealgar), or compare chemical differences in lacquerware crafts from different regions (such as Chu region versus Yangzhou), expanding the breadth of the project and enriching its connotations.

This project-based teaching design, themed "Exploring the Chemical Miracles in Chu-style Lacquerware," effectively situates high school phenol knowledge within the grand context of excellent traditional Chinese culture. Through scientific inquiry, students deciphered ancient crafts, and then infused them with new vitality using chemical wisdom, perfectly interpreting the connotation of "upholding the fundamentals while innovating." This is not merely a chemistry lesson, but a fusion journey of cultural inheritance and scientific exploration, effectively cultivating students' core competencies and sense of national identity.

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