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Reform and Path Exploration of Textile Dyeing and Finishing Technology Teaching Content under the Guidance of Green Sustainability

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ABSTRACT

The textile dyeing and finishing industry faces severe environmental challenges and pressure for a green transformation due to its high energy consumption and substantial pollutant emissions. To address the industry's urgent demand for professionals equipped with sustainability concepts, this study targets the disconnect between current textile engineering education and industrial development. It proposes a pedagogical reform framework for dyeing and finishing technology, centered on the core principles of green chemistry and the circular economy, with Life Cycle Assessment (LCA) as the unifying thread. This framework restructures the curriculum into five technical modules: (1) Sustainable textile raw materials (e.g., bio-based and recycled fibers) and green chemicals; (2) Clean production technologies, with a focus on water-saving processes like supercritical CO₂ waterless dyeing and digital printing; (3) Advanced treatment and resource utilization of dyeing and finishing wastewater; (4) Textile LCA and management systems; and (5) Intelligent process control of dyeing and finishing. Validated through a project-based learning (PBL) pilot of the LCA module, the framework is proven to effectively enhance students' systems thinking and practical ability to solve complex textile engineering problems. This research aims to provide a systematic pedagogical reform strategy for cultivating advanced engineering talent who meet the sustainable development requirements of the modern textile industry.

KEYWORDS

green sustainability, textile dyeing and finishing, engineering education, curriculum system, clean production

INTRODUCTION

The textile industry is a vital component of the national economy. Within this sector, dyeing and finishing processes are critical stages that impart color, texture, and functional properties to textile products. However, traditional dyeing and finishing techniques, particularly wet treatment processes, are characterized by

intensive water and energy consumption and generate substantial environmental pollution. Notably, the textile dyeing and finishing industry contributes approximately 20% of global industrial wastewater pollution [1]. The production of one ton of textiles typically requires approximately 200 tons of water, resulting in the discharge of considerable volumes of wastewater laden with dyes, chemical additives, and heavy metal ions and resulting in high levels of chemical oxygen demand [2]. In recent years, growing global awareness of environmental issues has prompted governments worldwide to implement increasingly stringent environmental regulations and standards [3,4], thereby intensifying the ecological compliance pressure on textile enterprises. Concurrently, consumer demand for sustainable textile products has surged at an unprecedented pace [5]. Brands and consumers are showing growing concern about the environmental footprint and ecological safety of textiles, compelling the entire supply chain to adopt greener, low-carbon, and circular production models.

The profound transformation of industrial sectors necessitates corresponding innovation in talent cultivation. In particular, the green transformation of the textile industry urgently demands the development of high-level engineering professionals who possess interdisciplinary knowledge spanning chemistry, environmental science, and related fields. These professionals must also be proficient in life cycle thinking, particularly life cycle assessment (LCA), and exhibit strong practical problem-solving abilities to address the complex challenges associated with sustainable textile production.

Although some academic institutions have begun to incorporate sustainability-related topics into their curricula, often in the form of elective courses or special lectures, such efforts remain fragmented and lack a cohesive, integrated structure that permeates the core curriculum of textile dyeing and finishing education [6,7]. There exists a notable gap in the pedagogical literature regarding the development of a comprehensive, multilevel framework that systematically restructures core teaching content around principles of sustainability, progressing from foundational knowledge to applied innovation [8,9]. This paper aims to address this gap by proposing a holistic educational framework that is not merely an auxiliary supplement, but a foundational restructuring of the curriculum. Specifically, the study undertakes a systematic analysis of the limitations inherent in traditional teaching content by examining deficiencies in knowledge structure, value orientation, and practical application. Based on this analysis, a reform framework is proposed that centers on green and sustainable development, aiming to make the curriculum more forward-looking, coherent, and practical. Furthermore, in alignment with the current context of higher engineering education

in China, the paper explores specific implementation strategies across various dimensions to ensure the effective application of this reform. To move beyond purely theoretical discussion, the study also introduces a pilot case of teaching reform, showcasing the initial application and effectiveness of the newly developed teaching module within an actual instructional setting. This practical demonstration serves as a reference model for other institutions. By aligning higher education in textiles with evolving industry needs, this study contributes a viable reform strategy for cultivating professionals equipped to address the challenges of the green transformation. Ultimately, it aims to strengthen the talent pipeline necessary for the sustainable development of the textile industry.

CURRENT STATUS AND CHALLENGES OF TEACHING CONTENT IN TEXTILE DYEING AND FINISHING TECHNOLOGY

Analysis of Traditional Teaching Content

Traditional core courses, such as *Dyeing and Finishing Technology* and *Dye Chemistry*, often exhibit several shortcomings in their teaching content.

Overemphasis on Conventional Processes and Underrepresentation of Green Technologies: A review of several widely used university textbooks reveals a persistent dominance of chapters dedicated to traditional dyeing methods for cotton and polyester within the curriculum [10]. By contrast, emerging green technologies, such as supercritical CO₂ dyeing, which eliminates the need for water and drying processes, and digital pigment printing, which significantly reduces water and chemical consumption, are typically addressed only briefly, often confined to a single subchapter.

A critical shortcoming in traditional textile education is the slow revision cycle of teaching materials, often resulting in a disconnect from current industry regulations, brand requirements, and supply chain sustainability standards. This gap is particularly evident in the continued inclusion of obsolete or noncompliant content in core curricula.

- **Restricted Chemical Example:** Many current syllabi continue to include auxiliaries containing alkylphenol ethoxylates (APEOs) as effective scouring or emulsifying agents. Despite their known toxicity as endocrine disruptors, APEOs have been included on the restricted substances lists of nearly all major global brands and regulatory frameworks, such as the Zero Discharge of Hazardous Chemicals (ZDHC) initiative [11]. However, their banned status is often not clearly emphasized in course materials, and

safer, commercially viable alternatives have not been systematically introduced.

- **Banned Dye Example:** The synthesis and application of some azo dyes that can degrade into carcinogenic aromatic amines are still taught as foundational topics in dye chemistry. Although these examples are valuable for understanding chemical principles, the curriculum often neglects to sufficiently underscore that such dyes are strictly prohibited under regulations, such as the EU's REACH legislation and the OEKO-TEX Standard 100 [12].
- **Lack of Instruction on Green Standards:** Systematic education on contemporary green chemistry standards and certification systems is lacking. Critical frameworks, such as the bluesign SYSTEM, which offers a comprehensive approach to safe chemical management, and the ZDHC Manufacturing Restricted Substances List, are rarely incorporated into core coursework [13,14]. Hence, students are insufficiently prepared to explore the compliance-driven demands of the modern textile industry.
- **Overreliance on "End-of-Pipe" Thinking:** The prevailing conceptual focus of the curriculum remains centered on "end-of-pipe" treatment, emphasizing how to manage wastewater, exhaust gases, and other pollutants after their generation. This reactive approach neglects the principles of "source control," which prioritize pollution prevention at the design and process levels through clean production techniques. Additionally, concepts, such as LCA, which encourage holistic, systems-level thinking across the entire product life cycle, are seldom integrated into teaching content.

Although the commonly used "paired" experimental model can reinforce fundamental operational skills, it is limited in its capacity to foster students' critical thinking and innovative design abilities. The substantial differences between traditional technologies and emerging green technologies (Table 1) further underscore the outdated nature of the current teaching content.

Table 1. Comparison of Traditional and Green Dyeing and Finishing Key Technologies

Comparison dimension	Traditional dyeing and finishing techniques	Green dyeing and finishing technology	Shift in teaching focus
Water consumption	High, the ratio of bath to water is usually 1:10–1:20.	Extremely low or no water (such as supercritical CO ₂ staining, vapor phase staining); low bath ratio (such as air flow staining, with a bath ratio of 1:3–1:5)	From "Water Conservation" to "Principles and Equipment of Waterless Processes"
Energy	High, dependent on	Low, low utilization of energy-saving processes, such	From "process energy

consumption	prolonged high-temperature fixation or drying	as cold rolling stacking and common temperature technologies like UV curing and plasma treatment	wet short steaming; conservation” to “the application of new energy forms (plasma, light energy)”
Chemical usage	Dependent on large amounts of inorganic salts, strong alkalis, and traditional additives (such as surfactants containing APEO)	Using biological enzymes, natural dyes, high fixation rate dyes, salt-free/low-salt dyeing technology, and biodegradable green additives	From “Chemical Application” to “Green Chemical Design, Selection and Compliance with Standards, such as ZDHC MRSL”
Pollution emissions	Produce wastewater with high chemical oxygen demand and high color intensity and are difficult to degrade	Reduce pollution at the source, and wastewater is easier to treat; some processes (such as digital printing) produce and extremely small amount of wastewater.	From “end-of-pipe governance” to “clean production and source control”
Process control	Dependent on manual experience, consistency and reproducibility are poor.	Digitalization and automation control, online monitoring of key parameters, reliance on data-driven process optimization	From “process operation” to “intelligent control, data analysis and application of MES system”
Core concept	Focus on product quality and production efficiency	Taking into account economic benefits, environmental impact and social responsibility, and following the principles of circular economy and life cycle assessment	From “Product Orientation” to “System Thinking across the Entire Lifecycle”

Limitations of Teaching Models and Methods

Current teaching methods largely depend on unidirectional knowledge transmission, with instructors delivering theoretical lectures from the podium. As a result, students have limited opportunities for active engagement, hands-on experimentation, or exploratory learning. This imbalance between theory and practice undermines the development of practical competencies and fails to cultivate the experiential insights

necessary for innovation in sustainable textile processing.

Most experimental courses are structured as verification exercises, designed primarily to replicate classical processes presented in lectures and achieve predetermined standard outcomes. Although this repetitive model can reinforce basic operational proficiency, it fails to foster critical thinking, creativity, and problem-solving skills. Moreover, such experiments do not adequately reflect the complexity and unpredictability of real-world industrial challenges, thereby limiting students' ability to engage with authentic engineering scenarios and innovate within the context of sustainable textile production.

The current curriculum remains highly fragmented, with subject areas, such as dyeing and finishing technology, chemistry, mechanical engineering, and automation taught in isolation. This artificial separation of disciplines hinders students from developing the integrative thinking and cross-disciplinary competencies required to address complex engineering problems. As a result, graduates often struggle to apply holistic solutions in real-world industrial contexts, particularly those involving sustainable and intelligent manufacturing systems.

CONSTRUCTION OF A GREEN AND SUSTAINABLE-ORIENTED TEACHING CONTENT REFORM FRAMEWORK

To address these challenges, a systematic reorganization of the existing teaching content is necessary. This paper proposes a new “three-level, five-module” teaching content system based on the core concept of green sustainability. The system divides the cultivation of knowledge, abilities, and qualities into three progressive levels and is implemented through five specific teaching modules (Figure 1).

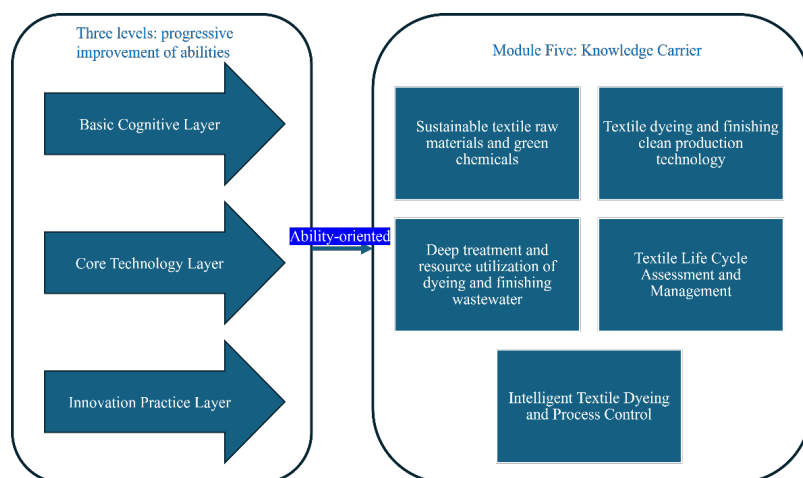


Figure 1. “Three-Level, Five-Module” Teaching Content System Diagram

Guiding Ideology and Core Concept of the Reform

- Core Concept: Grounded in the *Twelve Principles of Green Chemistry* [15] and the *Circular Economy* (reduction, reuse, and recycling), the concept of sustainable development is embedded as the central guiding ideology throughout the curriculum.
- Main Thread of Thinking: The LCA approach serves as the overarching framework across all teaching modules, guiding students to adopt a systems perspective and to evaluate technologies, products, and processes in terms of their environmental, economic, and social impacts.
- Capability-Oriented Approach: The curriculum emphasizes the development of *multidisciplinary integration* and *systems engineering* thinking, aiming to equip students not only with the ability to acquire knowledge, but also to apply it effectively and drive innovation.

“Three-Level, Five-Module” New Teaching Content System

- The “three levels” define a progressive pedagogical approach to capability development, whereas the “five modules” function as substantive carriers of disciplinary knowledge. These two components do not correspond in a simple one-to-one manner. The three-level structure is dynamically integrated and applied in a spiral progression within each of the five modules. In practice, this means that each module guides students through a continuum, from foundational understanding (Cognitive Level), to mastery of core principles (Technology Level), and ultimately to the creative application of knowledge (Innovation Level).
- Three Levels
 - Foundation Cognitive Level: This level aims to develop students’ broad understanding of the interconnections between textile dyeing and finishing processes and the ecological environment. It emphasizes the necessity and urgency of the green transformation within the industry.
 - Core Technology Level: This level provides systematic instruction in the key technologies, fundamental principles, and practical application methods of green dyeing and finishing. It constitutes the core of the curriculum content.
 - Innovative Practice Level: Through project-based learning (PBL) and comprehensive experimental design, this level seeks to cultivate students’ integrative and innovative capabilities, enabling them to apply acquired knowledge to solve real-world, complex engineering problems.

- Five Modules
- (1) Sustainable Textile Raw Materials and Green Chemicals: Exploring Sustainability from the Source.
- (2) Textile Dyeing and Finishing Clean Production Technology: Focusing on Pollution Reduction during the Process.
- (3) Deep Treatment and Resource Utilization of Dyeing and Finishing Wastewater: Emphasizing Efficient End-of-Pipe Governance and Recycling.
- (4) Textile Life Cycle Assessment and Management: Establishing a Systematic Environmental Management Tool Approach.
- (5) Intelligent Textile Finishing and Process Control: Integrating Information Technology to Enhance Efficiency and Sustainability.

Integration of Levels and Modules: A Pedagogical Example

The three levels and five modules are dynamically integrated. In each knowledge module, teaching is structured to guide students progressively from the Foundation Cognitive Level (understanding the “why” through case studies), through the Core Technology Level (mastering the “what” and “how” of key principles and equipment), to the Innovative Practice Level (applying knowledge to solve complex problems through PBL). This structure ensures that each module completes a full learning cycle, from knowledge acquisition to innovation application.

DETAILED EXPLANATION OF THE CORE MODULES OF CURRICULUM REFORM

Module One: Sustainable Textile Raw Materials and Green Chemicals

This module serves as the entry point for sustainable practice, with a focus on input materials. The teaching content is structured around clearly defined learning objectives to ensure depth and coherence.

- Sustainable Fibers: The goal is to move beyond mere description to a multi-dimensional analysis of each fiber type.
 - Lyocell: Key learning objectives include: (1) Chemical Engineering Principles: Analyze the closed-loop production process and focus on the non-toxic *N*-methylmorpholine *N*-oxide solvent system and its >99% recovery rate. (2) Material Science: Understand the relationship between spinning conditions and the controllable fibrillation properties of the fiber. (3)

Environmental Science: Quantitatively compare the water footprint and land usage of Lyocell versus conventional viscose and cotton.

- Bio-based Synthetics (e.g., PLA): Key topics will cover: (1) *Polymer Chemistry*: Examine the polymerization of lactic acid from renewable resources like corn starch. (2) *Environmental Engineering*: Understand the specific conditions required for industrial composting and explain why it is not typically home-compostable. (3) *Textile Engineering*: Address the technical challenges related to PLA's low melting point during thermal processing and its limited dyeability with conventional dyes.
- Recycled Fibers (e.g., rPET): The curriculum will differentiate the following: (1) *Mechanical Recycling*: Analyze the process flow, energy inputs, and the inevitable degradation of polymer viscosity and properties over multiple cycles. (2) *Chemical Recycling*: Study the principles of glycolysis or methanolysis to depolymerize PET back to monomers, and the associated challenges of purification and cost.
- Green Chemicals
 - Natural Dyes: Learning objectives include not only their application but also: (1) analytical chemistry: methods for extracting and purifying colorants from natural sources. (2) dyeing chemistry: understanding the role of different mordants and their respective environmental profiles in achieving color fastness.
 - Enzymes: The curriculum will focus on the following: (1) Biochemistry: the mechanism of enzymatic hydrolysis (e.g., cellulase for biopolishing cotton). (2) Process engineering: optimizing process parameters, such as pH, temperature, and time to maximize enzyme activity and efficiency.

Module 2: Textile Dyeing and Finishing Clean Production Technology

This module forms the core of reducing process-related pollution. The teaching content should focus on introducing the following:

- Water-Saving/No-Water Dyeing Technology: Comprehensive explanation of the principles, equipment, application scope, and industrial implementation of supercritical CO₂ fluid dyeing for hydrophobic fibers, such as polyester [16]; introduction to the principles and latest developments of technologies, such as vapor dyeing, plasma graft modification and functional finishing, and UV-

cured coating printing and dyeing.

- **High-Efficiency Short-Process Technology:** Introduction to short-process techniques, such as one-step enzymatic pretreatment and one-bath scouring; high-fixation reactive dyes and low-salt/no-salt dyeing technologies; energy-saving processes, such as cold pad-batch dyeing.
- **Digital and Automated Dyeing Technology:** Introduction to digital printing technology and a comparative analysis of its advantages and limitations relative to traditional printing; overview of advanced equipment, including automated dye and chemical dispensing systems and small-bath ratio air-flow/liquid-flow dyeing machines.

Module Three: Deep Treatment and Resource Utilization of Dyeing and Finishing Wastewater

This is a crucial step in achieving a circular economy. The teaching content should include:

- **Advanced Wastewater Treatment Technology:** Building upon traditional physical–chemical and biochemical treatment methods, this section focuses on the application of advanced oxidation technologies (such as the Fenton process and ozone oxidation) and membrane separation technologies (such as nanofiltration and reverse osmosis) for treating high-concentration and recalcitrant dyeing and finishing wastewater, as well as the integration of multiple treatment methods.
- **Resource Recovery Technology:** This section explains the technical principles and engineering applications related to the recovery of water, thermal energy, alkali (e.g., alkaline finishing solutions), and specific dyes (e.g., indigo) from wastewater generated in printing and dyeing processes. The objective is to cultivate students' awareness and understanding of resource recovery within sustainable manufacturing systems.

Module Four: Textile Life Cycle Assessment (LCA) and Management

This module serves as a tool for quantifying and systematizing the concept of sustainability. LCA evaluates the environmental impacts associated with all stages of a product system, from raw material acquisition to final disposal, through a standardized set of procedures (Figure 2). The teaching content should include:

- **LCA Theory and Practice:** Teach the basic framework of LCA (including goal and scope definition, inventory analysis, impact assessment, and interpretation), and introduce the fundamental operations of mainstream LCA software, such as SimaPro and GaBi.

- **Case Analysis:** Organize students into groups to conduct a simplified LCA case study on a cotton T-shirt or a pair of jeans. Guide them in calculating the carbon and water footprints from “cotton field to closet,” to develop a clear understanding of the environmental impact at each stage of production.
- **Standards and Certifications:** Introduce major sustainability-related standards and certification systems, including the Global Organic Textile Standard, the OEKO-TEX system (with emphasis on the “Made in Green” label), and the Higg Index. This content enables students to understand how enterprises implement sustainability management and conduct environmental information disclosure.

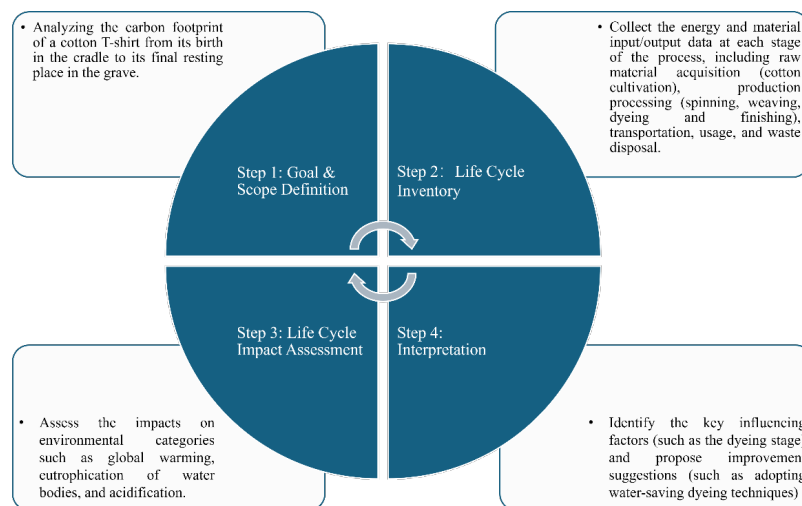


Figure 2. Flowchart of the Life Cycle Assessment (LCA) process for textiles

Module Five: Intelligent Dyeing and Process Control

This module represents the future direction for improving the efficiency and stability of the dyeing and finishing industry. The teaching content should include:

- **Online Monitoring and Data Acquisition:** Introduce sensor technologies for real-time monitoring of key parameters, such as temperature, pH, and dye concentration, during the dyeing and finishing processes.
- **Intelligent Process Optimization:** Incorporate concepts from big data and artificial intelligence (AI) to demonstrate how historical production data can be used to optimize dyeing formulations and process curves through algorithmic modeling. This increases first-pass yield and reduces rework rates.

- Information Management System: Introduce the application of Manufacturing Execution Systems and Enterprise Resource Planning in modern dyeing and finishing enterprises. Discuss how these systems facilitate transparent, traceable, and refined management of production processes.

PRELIMINARY PRACTICAL CASE STUDY: A PBL-BASED TEACHING PILOT FOR THE LCA MODULE

To verify the practical feasibility and pedagogical effectiveness of the proposed “three-level, five-module” teaching system, we conducted a preliminary teaching reform pilot during the 2023–2024 academic year. The pilot was implemented in the course *Textile Processing II*, offered to third-year students majoring in Textile Engineering at a selected university. The reform focused on Module Four of the new system, *Textile Product Life Cycle Assessment (LCA) and Management*, as the initial entry point for implementation.

Pilot Design and Implementation

The implementation followed a standard project-based learning (PBL) process. Students were organized into teams and received foundational instruction on LCA theory and relevant software tools. Under the guidance of an interdisciplinary faculty team, they then conducted an eight-week research project. The assessment approach was restructured to include project reports, oral defenses, and progress summaries, thereby shifting the emphasis from traditional examinations to a more holistic evaluation of students’ comprehensive competencies.

Pilot Results and Feedback

After the conclusion of the pilot program, the effectiveness of the teaching reform was evaluated using a combination of questionnaire surveys, focus group interviews, and an assessment of the quality of the final project reports.

- Qualitative Feedback:

Establishment of Systems Thinking: Students generally reported that by independently completing an LCA case study, their perception of dyeing and finishing processes shifted from viewing them as isolated operations to understanding them as components within an interconnected supply chain system. They developed a deeper appreciation for the concept of “cradle to grave.” As one student noted during an interview: “Previously, I only cared about whether the color was dyed correctly. Now, when I see a piece of clothing, I subconsciously think about its water footprint and carbon footprint. I truly understand the weight

of 'green'."

Stimulation of Innovative and Critical Thinking: Compared with traditional "formula–operation–color matching" verification experiments, the open-ended nature of PBL presented greater challenges. Students were required to sift through extensive information, critically analyze contradictory sources, and defend their chosen technical approaches, significantly enhancing their ability to solve complex engineering problems.

Enhancement of Industry Awareness: Engagement with sustainability standards, such as the Higg index, and the examination of corporate environmental reports enabled students to perceive a clear connection between course content and current industry practices. This alignment with real-world developments fostered a heightened sense of motivation and strengthened students' identification with future career paths in the green textile industry.

- **Quantitative Results:**

Based on the submitted project reports, over 90% of the student groups successfully applied the LCA framework, clearly and systematically presented their research processes and findings, and proposed insightful process improvement suggestions grounded in data (for example, "*Using the cold rolling stacking process can reduce the carbon footprint in the dyeing stage by approximately 60%*").

After the course concluded, a questionnaire survey was administered. The results indicated that over 85% of the students believed the PBL model was more effective than traditional teaching methods in stimulating their interest in learning. Moreover, over 90% of the students considered the LCA module essential for understanding the sustainable development of the textile industry.

Challenges and Reflections

The pilot also revealed several challenges, largely aligning with the difficulties anticipated at the outset of the reform.

First, some students encountered difficulties in learning the LCA software and handling uncertain data during the early stages of the project, which placed higher demands on the instructors' knowledge and support. To address this, future iterations could incorporate more guided practice sessions on software operation and provide a standardized basic dataset to lower the initial learning threshold.

Second, effective collaboration within the interdisciplinary teaching team required greater advance planning and coordination to ensure a coherent knowledge framework and consistent instructional guidance.

Despite these challenges, the small-scale pilot successfully demonstrated the feasibility of integrating

advanced green concepts into core professional courses. It validated the effectiveness of innovative teaching methods, such as PBL, in fostering students' systems thinking and practical innovation abilities, while providing valuable insights for scaling and replicating similar reforms in other modules.

EXPLORATION OF THE IMPLEMENTATION PATH OF TEACHING REFORM

The implementation of such a comprehensive reform constitutes a systematic undertaking that demands coordinated efforts across multiple dimensions. Its successful realization requires not only a clearly defined roadmap, but also proactive strategies to address the institutional, administrative, and financial challenges that inevitably arise.

Strategic Faculty Development and Team Building

The success of this reform ultimately hinges on the capabilities of the teaching staff. Recognizing that expecting traditional textile engineering faculty to independently master complex and interdisciplinary fields, such as environmental chemistry, data science, or LCA, which is a long-term and multi-pronged faculty development strategy, is unrealistic is essential.

Fostering a Culture of Internal Co-Learning

Before seeking external resources, internal capacity must be cultivated. This initial step is sustainable and cost effective.

- Peer-to-Peer “Micro-training” Workshops: Rather than requiring lengthy external training for all faculty, people with existing expertise can be incentivized to lead short and focused workshops for colleagues. For example, a professor with a background in environmental science can offer a three-session workshop on *Fundamentals of Wastewater Toxicology*, whereas a tech-savvy colleague might introduce *Python for Textile Process Data Analysis*.
- Structured Interdisciplinary Journal Clubs: Establish a regular journal club focused on reviewing cutting-edge research in sustainable textiles. This promotes continuous, collaborative learning and helps ensure the entire faculty team remains current with technological advancements in a structured, consistent manner.

Targeted External Training and Immersion

External training should be strategic and focused on acquiring specific, high-priority skills, rather than general “visiting studies.”

- “Sabbatical Sprints” on Specific Tools: Instead of traditional year-long sabbaticals, faculty can participate in short-term (e.g., 1–2 week) intensive courses focused on mastering specific tools, such as SimaPro or GaBi, for LCA, or advanced statistical software used in the design of experiments.
- Industry “Teacher Externships”: Establish partnerships that allow faculty to spend several weeks embedded in the R&D or sustainability departments of leading enterprises. This offers hands-on exposure to the implementation of green technologies and management systems, yielding a far more practical and immersive learning experience than typical academic visits.

Strategic Co-Teaching and Hiring

The formation of interdisciplinary teams is crucial and can be achieved through a combination of collaborative teaching and strategic hiring.

- Emphasis on Co-teaching: This is one of the most effective forms of on-the-job training. A module, such as “Intelligent Process Optimization,” can be co-taught by a traditional dyeing and finishing professor alongside a computer science faculty member. The textile expert provides domain context and challenges, while the data scientist contributes algorithmic and AI expertise, creating a valuable learning experience for both students and instructors.
- Strategic, Long-Term Hiring: While bringing in interdisciplinary talent is a long-term goal, recruitment should be targeted to address specific curriculum gaps. For instance, the next faculty hire can be a polymer chemistry expert with a focus on biodegradable materials to directly support Module 1.

This portfolio of strategies offers a realistic and sustainable approach to faculty development, blending low-cost internal initiatives with high-impact external experiences and collaborative teaching models to gradually build the interdisciplinary capacity required for successful reform.

Strategies for Building a Practical Teaching Platform

Acknowledging the high cost of cutting-edge equipment, a multifaceted and pragmatic strategy is essential, one that goes beyond simply “seeking funds.” This strategy should combine internal innovation, strengthened industry collaboration, and inter-institutional resource sharing to maximize access and sustainability.

Tiered Approach to In-House Lab Development

Instead of aiming directly for expensive, full-scale production equipment, a more cost-effective, phased approach can be adopted:

- **Principle–Demonstration Equipment:** For complex technologies, such as supercritical CO₂ dyeing, the core pedagogical goal is to grasp the underlying principle rather than perform full-scale fabric dyeing. Institutions can invest in or fabricate low-cost, high-pressure viewing cells that allow students to observe CO₂ reaching its supercritical state and examine its solvent properties. This approach effectively conveys the concept at a fraction of the cost.
- **“Lab-on-a-Bench” Kits:** For processes, such as enzymatic treatment or natural dyeing, low-cost, self-contained experimental kits can be developed. These kits might include various enzymes, natural dye extracts, fabric swatches, and basic measurement tools (e.g., portable colorimeters), enabling hands-on and replicable experiments without the need for large machinery.
- **Targeted Acquisition of Pilot-Scale Equipment:** Efforts to secure funding should focus on acquiring versatile, small-scale pilot equipment, such as multi-function plasma processors or small-bath-ratio dyeing machines, that can support a wide range of teaching and research applications.

Deepening Industry-Academia Integration beyond Joint Laboratories

While joint laboratories offer value, more flexible forms of collaboration can often provide equally practical and accessible real-world experience.

- **“Embedded” Workshops at Enterprises:** Partner with companies to host small student groups in their R&D or QC labs for short, intensive workshops. Guided by industry engineers, students gain hands-on experience with advanced equipment while working on focused projects, offering real-world exposure that university laboratories often cannot replicate.
- **Practice through Industrial Data Analysis:** When direct access to equipment is not feasible, partner enterprises can share real production datasets from intelligent dyeing systems. Students engage in data-driven projects, modeling processes, identifying inefficiencies, or proposing optimizations, thus gaining valuable data literacy and process analysis skills at minimal cost.

Inter-Institutional Collaboration and Resource Sharing

The reform promotes the widespread adoption of the PBL model and case-based analysis to foster critical

thinking. Crucially, assessment methods must shift from traditional knowledge-recall exams to evaluations centered on competencies. This can be accomplished by implementing detailed grading rubrics for projects, designed to assess higher-order skills, such as systems thinking, data analysis, and innovation, thereby ensuring greater transparency, fairness, and validity in the evaluation process.

Innovation in Teaching Methods and Assessment of Higher-Order Skills

Promoting the PBL Teaching Method: Focusing on a specific topic (such as *The Green Rebirth of a Pair of Jeans*), the PBL model is implemented to engage students in team-based exploration of the full product lifecycle. This includes raw material selection, process design, LCA, and cost calculation, fostering comprehensive and applied learning.

Introducing Case Studies: Carefully selected case studies, both successful and unsuccessful examples of green transformation from domestic and international enterprises, are analyzed in class. These are used to spark structured discussion and critical reflection, enhancing students' analytical thinking and decision-making abilities.

Reforming Assessment Methods: from Knowledge Recall to Competency Evaluation: The development of higher-order skills and assessment must move beyond traditional closed-book exams focused on rote memorization. Although such exams may still be used in the evaluation of foundational knowledge (e.g., accounting for 20%–30% of the final grade), the primary focus must shift to competency-based evaluation. The most effective way to achieve this is through the use of detailed grading rubrics for project-based assignments. For a comprehensive project, such as the LCA case study described in Section 5, evaluation should not rely on a single holistic score. Instead, it should be based on a rubric that deconstructs complex competencies, such as systems thinking, into specific, observable, and measurable indicators. An example rubric structure is provided in Table 2.

Table 2. Sample Grading Rubric for Project-Based Assessment

Assessment Criterion	Core Competency Assessed	Description of "Excellent" Performance (Example)	Proportion (Example)
System Definition &	System Engineering Thinking	The project clearly and logically defines the system boundaries ("cradle to gate" or "cradle to grave"). All significant life cycle stages,	20%

Scoping		inputs, and outputs are identified and justified with reference to LCA standards (e.g., ISO 14040).	
Data Integrity & Analysis	Research & Analytical Skills	The team effectively utilizes academic literature and industry databases (e.g., Ecoinvent) to gather high-quality data. Quantitative analysis is accurate, transparent, and presented clearly in tables and figures.	20%
Integration of Knowledge	Multidisciplinary Integration	The report seamlessly integrates principles from textile chemistry (process details), environmental science (impact assessment), and basic economics (cost implications). Conclusions are supported by evidence from these different fields.	20%
Critical Interpretation & Innovation	Innovation & Critical Thinking	The team not only presents results but also critically interprets the “hotspots” of environmental impact. They propose creative, well-justified, and feasible technical or process improvements and thoughtfully discuss the limitations of their own study.	25%
Teamwork & Communication	Collaboration & Professional Skills	The final written report is coherent, professionally structured, and clearly written. The oral defense is well organized, all team members contribute effectively, and the team provides clear, confident answers to questions.	15%

Implementation of the rubric:

- **Transparency:** The rubric will be provided to students at the outset of the project. This ensures that assessment criteria are fully transparent and transforms the rubric from a mere grading tool into a *learning guide*. It clearly communicates what constitutes high-quality work and guides students in aligning their efforts with the expected outcomes.
- **Formative Feedback:** The rubric also serves as a tool for formative assessment. For instance, the “System Definition & Scoping” criterion can be evaluated midway through the project, enabling instructors to offer targeted feedback.
- **Reliability and Validity:** By deconstructing a complex task into well-defined criteria, the rubric enhances the consistency of evaluation, different instructors are more likely to assign similar scores for the same

work, thereby improving reliability. At the same time, it ensures construct validity by directly measuring the specific higher-order skills the course aims to cultivate.

This rubric-based approach offers a structured, transparent, and pedagogically sound framework for assessing the complex competencies emphasized in this curriculum reform. It elevates evaluation from subjective judgment to an evidence-based process grounded in clearly articulated expectations.

Strengthening Collaboration among Industry, Academia, and Research Institutions for Student Education

Enterprise Experts in the Classroom: Establish a database of industry experts and systematically recruit enterprise engineers and senior executives with extensive experience in green chemical development, clean production management, and environmental certification. These experts will serve as part-time professors or industry mentors, delivering specialized lectures or short-term courses that bridge academic learning with industrial practice.

Joint Project-driven Approach: Centered on the key technical challenges faced by the dyeing and finishing industry during its green transformation, such as enhancing the color fastness of new natural dyes or treating recalcitrant wastewater, universities and enterprises can establish collaborative research projects. Senior undergraduate and graduate students will be encouraged to participate in these projects, gaining practical experience through “hands-on” research that strengthens their innovation capabilities and problem-solving skills.

CONCLUSIONS

In response to the global push for sustainable development and the pressing need for green transformation within the textile dyeing and finishing industry, the traditional curriculum of textile engineering is increasingly inadequate. This paper systematically identifies the shortcomings of current teaching content and proposes an innovative curriculum framework centered on the core concepts of green chemistry and the circular economy, with LCA serving as the unifying thread. The proposed system aims to fundamentally restructure students' knowledge base and competency profile, fostering a new generation of interdisciplinary professionals equipped with both a forward-looking vision and the ability to address complex environmental engineering challenges in the textile sector.

Through a preliminary teaching pilot of the core module *Textile Life Cycle Assessment*, this study validated the positive impact of the proposed curriculum reform. Implemented within a PBL framework, the pilot

demonstrated that the new teaching model effectively stimulates students' initiative and fosters a spirit of innovation. The reform yielded significant improvements in students' abilities in systems thinking, collaborative teamwork, and the application of theoretical knowledge to practical problems, thereby providing initial evidence of the feasibility and value of the newly constructed teaching system.

Although this study has yielded promising exploratory results, we fully acknowledge its limitations, many of which also point toward important directions for future research. First, the research design lacks a control group. This pilot did not incorporate an A/B test comparing the new teaching model with traditional instruction conducted in parallel. As a result, while the study demonstrates the effectiveness of the reformed model, it does not allow for a rigorous, quantitative comparison to determine its superiority over conventional approaches. Second, the scope of the sample is limited. The pilot was confined to a single institution, one semester, and one module, which restricts the generalizability and representativeness of the findings. Further research is needed to test the model across diverse institutional contexts and within a more comprehensive curriculum framework.

To further advance this teaching reform and obtain more reliable, generalizable conclusions, we propose the following actions: (1) Optimize the research design: Future implementations should incorporate both experimental and control groups to enable rigorous comparative studies. By employing more scientific and quantitative evaluation methods, the relative effectiveness of the reformed teaching model can be more accurately assessed. (2) Expand the research scope: The teaching system should be extended to multiple types of textile institutions, including those at different academic levels and regions. A 2–3 year longitudinal study should be conducted to comprehensively evaluate the cumulative impact of the five-module system on students' long-term competency development. Furthermore, to ensure the successful implementation and sustainability of this reform, systematic progress must be achieved across four critical dimensions: Faculty development in green concepts and interdisciplinary capabilities; Intelligent and green upgrades to the practical teaching infrastructure; Ongoing pedagogical innovation, including broader application of PBL and competency-based assessment models; Deepened industry–academia–research collaboration, enabling real-world problem-solving and joint talent cultivation. The ultimate goal is to establish a high-quality talent training paradigm that can continuously provide core strength for the sustainable development of China's textile industry and contribute to global sustainability efforts.

Author Contributions

Zhenguo Shang designed, collected and analyzed the data, and drafted the manuscript. Zhenguo Shang conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Zhenguo Shang participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflict of Interest

The author declares no conflict of interest.

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Availability of Data and Materials

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