

Construction and Practice of a Multiple Evaluation System for the Course Materials Analysis and Characterization Experiments Based on the 5E Teaching Model

Wei Wen*, Jianhao Zhao, Hongyan Li, Jiayi Xu

School of Chemistry and Materials Science, Jinan University, Guangzhou, Guangdong, China

**Corresponding Author*

Abstract: To address problems in Materials Analysis and Characterization Experiments (large classes, limited instruments, single evaluation, result-orientation), this study built a multiple evaluation system based on the 5E model, covering the whole teaching process. It includes six first-level dimensions (interest / participation, exploration / operation, explanation / understanding, extension / innovation, collaboration / communication, reflection / improvement) and 24 second-level indicators, with weights determined by AHP. Teacher observation, student self-evaluation, peer evaluation, and operational skill scoring sheets were developed, using Wenjuanxing and Excel for data collection and feedback. Practice showed improved operational standardization, class participation, active thinking, and reflective awareness. Compared with the control group, the experimental group's excellent operation rate increased by 18.6%, and the excellent rate of final comprehensive performance rose by 21.5 %. Embedding evaluation into the whole 5E process promotes coordination of teaching, learning, and assessment, and offers a reference for reform in university lab courses.

Keywords: 5E Teaching Model; Materials Analysis and Characterization Experiments; Multiple Evaluation; Process Evaluation; Reform of Experimental Teaching

1. Introduction

With the continuous advancement of the “New Engineering” initiative, higher education has placed increasing emphasis on students' practical ability, problem-analysis ability, and innovative awareness. Materials Analysis and Characterization Experiments is an important laboratory course for the major of Materials Science and Engineering. Relying on expensive

large-scale instruments such as scanning electron microscopes, X-ray diffractometers, and thermogravimetric analyzers, the course is mainly intended to train students to comprehensively apply multiple analytical methods to characterize, judge, and interpret materials. Compared with ordinary basic laboratory courses, this course is characterized by expensive equipment, high operational requirements, and complex teaching organization, which places higher demands on both classroom management and evaluation methods [1,2].

In actual teaching, this course still faces several prominent contradictions. First, the class size is usually 50-60 students, whereas the number of expensive large-scale instruments is limited. As a result, within limited class hours, students can often complete only part of the operational procedures and find it difficult to independently experience the whole experimental process. Second, the current evaluation method is too narrow. It mainly relies on lab reports and attendance. Thus, it fails to fully assess students' instrument operation, participation, collaboration, communication, or experimental reflection. Third, feedback on evaluation results is usually given only after the course finishes. This prevents teachers from adjusting their teaching in time based on student performance. It also makes it hard for students to correct their problems promptly in subsequent experiments [3,4].

The 5E teaching model originates from constructivist learning theory and includes five stages, namely Engagement, Exploration, Explanation, Elaboration, and Evaluation. It emphasizes that students achieve knowledge construction through observation, operation, discussion, and reflection in authentic situations [5]. Existing studies have shown that the 5E model is applicable to science and engineering

education [6]. However, its systematic application in university-level materials analysis laboratory courses remains limited, especially with regard to the construction of evaluation systems matching the course process. Therefore, this study targets the course Materials Analysis and Characterization Experiments. Based on course reform practice since 2025, it built a multiple evaluation system. The system emphasizes process, multiple subjects, and feedback. The study also examined its application effects.

2. Design and Construction of the Multiple Evaluation System

2.1 Design Concept of the Evaluation System

To address the problem of “emphasizing results while neglecting process” in traditional laboratory-course evaluation, the following aspects were mainly considered in designing the evaluation system.

First, the evaluation content was made to correspond as closely as possible to the 5E teaching process, so that evaluation could be used not only for final grade determination but also for learning guidance during class. Second, the focus of evaluation was shifted forward to cover the whole life cycle, including pre-class

preparation, in-class operation, discussion and expression, and post-class reflection. Third, a multi-subject evaluation mechanism was introduced by adding student self-evaluation and peer evaluation on the basis of teacher evaluation so as to obtain more complete learning information. Fourth, quantitative and qualitative methods were combined, with clear behavior-anchored standards and written feedback provided.

2.2 Construction of the Evaluation Indicator System

Based on the 5E model and the characteristics of materials analysis experiments, six first-level evaluation dimensions were established in this study (see Table 1) [7,8]. “Interest and participation”, “exploration and operation”, “explanation and understanding”, and “extension and innovation” correspond to the first four core stages of the 5E model. “Evaluation”. However, evaluation was not a single outcome-oriented dimension. Instead, it was embedded throughout the whole process via self-evaluation and peer evaluation. In addition, considering the highly collaborative nature of large-instrument experiments, the dimension of “collaboration and communication” was added.

Table 1. Correspondence between the 5E Teaching Model and the Evaluation Dimensions

5E Phase	Evaluation Dimension	Core Connotation
E1 Engagement	Interest and Participation	Pre-class preparation, class engagement, awareness of problem identification
E2 Exploration	Exploration and Operation	Experimental design, instrument operation standards, data collection, handling of unexpected anomalies
E3 Explanation	Explanation and Understanding	Mastery of instrument principles, spectral/data analysis, scientific interpretation of results
E4 Elaboration	Elaboration and Innovation	Knowledge transfer and application, innovative and extended thinking, multi-instrument integration thinking
Throughout	Collaboration and Communication	Team task division, logical communication and expression, peer support spirit
Throughout	Reflection and Improvement	Self-evaluation of experiments, summary and reflection on errors, continuous improvement of subsequent plans

On the basis of the first-level dimensions, 24 second-level indicators were further refined, and each indicator was matched, as far as possible, to specific behaviors that could be observed and judged. For example, under the dimension of “exploration and operation”, emphasis was placed on whether students could complete sample preparation, parameter setting, data acquisition, and safety protection in a standardized manner. For key indicators, behavior-anchored rating descriptions were

adopted to clarify the behavioral performance corresponding to different score ranges, so as to reduce subjectivity in scoring (see Table 2).

When calculating the comprehensive score, the score of each dimension was first normalized to a 100-point scale and then multiplied by its corresponding weight. Through behavior anchoring, the scoring criteria were transformed from abstract judgments into observable behaviors, thereby reducing the influence of subjective impressions on grading and

improving scoring consistency among different teachers.

Table 2. Evaluation Indicators and Behavior-Anchored Criteria for the Dimension of “Exploration and Operation” (Excerpt)

Second-level Indicator	A Level (90%-100%)	B Level (75%-89%)	C Level (60%-74%)
Instrument Operation Standardization	Independently and proficiently completes start-up, parameter setting, and testing; complies with safety regulations	Basically completes independently, with occasional reminders needed for a few steps; no safety violations	Completes under guidance; operation is unfamiliar with minor non-standard practices
Abnormality Handling	Actively identifies causes upon encountering abnormalities and takes effective corrective measures	Analyzes with prompts and makes some adjustments when abnormalities occur	Completely relies on the teacher when abnormalities occur; lacks initiative

2.3 Weight Determination and Calculation Model

Different dimensions contribute differently to the attainment of course objectives. Considering that Materials Analysis and Characterization Experiments primarily emphasizes students' instrument operation ability and experimental analysis ability, the analytic hierarchy process (AHP) was used to assign weights to the six first-level dimensions. Specifically, five front-line teachers and teaching supervisors with long-term experience in laboratory teaching were invited to construct judgment matrices, and consistency tests were performed to determine the final weights [9]. The calculated random consistency ratio (C.R.) of the five expert judgment matrices was less than 0.1, indicating that the weight allocation was statistically

reasonable.

The results showed that the weights of the six dimensions were 25% for exploration and operation, 20% for explanation and understanding, 20% for extension and innovation, 15% for interest and participation, 10% for collaboration and communication, and 10% for reflection and improvement. Accordingly, the process evaluation score was calculated as:

$$Sp=0.25S_{exp}+0.20S_{expl}+0.20S_{ext}+0.15S_{eng}+0.10S_{col}+0.10S_{ref} \quad (1)$$

where Sp is the process evaluation score, and S_{exp} , S_{expl} , S_{ext} , S_{eng} , S_{col} , and S_{ref} represent the normalized scores of the six dimensions, respectively.

3. Development of Evaluation Tools and Construction of the Data Platform

Table 3. Mapping Matrix of Evaluation Data Sources to the Six First-Level Dimensions

First-level Evaluation Dimension	Main Data Sources (Weight Proportion)
Interest and Participation	Teacher's in-class critical incident records (70%) + Self-assessment scale (30%)
Exploration and Operation	Teacher's standardized operation scoring sheet (100%)
Explanation and Understanding	Teacher's classroom Q&A/discussion records (80%) + Lab report (20%)
Elaboration and Innovation	Lab report / after-class extended tasks (70%) + Self-assessment scale (30%)
Collaboration and Communication	Anonymous peer evaluation (100%), Teacher-assisted observation
Reflection and Improvement	Student self-reflection scale (100%)

After completing the design of the evaluation indicators, structured scales corresponding to different evaluation subjects were further developed. To avoid readers misunderstanding “evaluation subjects” and “evaluation dimensions” as parallel concepts, the data collection focus of each evaluation tool was clearly defined: the teacher observation scale mainly covered objective operational dimensions such as “exploration and operation” and “explanation and understanding”; the student self-evaluation scale focused on internal cognitive dimensions such as “reflection and

improvement” and “extension and innovation”; and the peer evaluation scale mainly targeted classroom interaction dimensions such as “collaboration and communication” and “interest and participation”. The mapping relationship between each data source and the six first-level dimensions is shown in Table 3.

3.1 Design of Teacher Observation, Self-Evaluation, and Peer-Evaluation Scales

3.1.1 Teacher observation scale

Teacher evaluation was mainly used to record students' actual classroom performance.

Considering the fast pace of large-instrument laboratory sessions, it would be difficult for teachers to completely record all behaviors of every student item by item. Therefore, the study adopted the method of “key event recording + baseline score”: behaviors that were particularly outstanding or obviously problematic were recorded as key events, while routine performance was assigned a baseline score. This method preserved useful information from process observation while also reducing the burden of teacher recording [10].

3.1.2 Student reflective self-evaluation scale

Student self-evaluation was arranged after each experiment and was conducted in the form of a five-point Likert scale. The content covered pre-class preparation, understanding of principles, rationale for parameter setting, problem solving, result interpretation, and subsequent improvement. Example items included: “I carefully read the relevant materials and understood the purpose of the experiment before class”; “I clearly understood what problem this experiment was intended to solve”; “When encountering difficulties, I tried different methods to solve them”; and “I know in which aspects I still need to improve.” The self-evaluation results were included in the process score and also served as a reference for teachers to understand students’ learning status [11].

3.1.3 Anonymous peer-evaluation scale

Peer evaluation was mainly used in group experiments and discussion sessions and was completed anonymously. The purpose was not simply to compare students with one another, but to understand their actual performance in group task assignment, expression of opinions, cooperative awareness, and task completion. Through peer evaluation, teachers could identify differences in students’ participation more clearly and reduce the phenomenon of “observing without participating”.

3.2 Standardized Operational Skill Scoring Sheets

For seven types of core instruments, including the scanning electron microscope (SEM), X-ray diffractometer (XRD), and thermogravimetric analyzer (TGA), standardized operational skill scoring sheets were formulated. Taking the SEM as an example, the scoring contents included sample mounting, startup and vacuum pumping, high-voltage parameter setting, image focusing

and astigmatism correction, spectrum/image acquisition and output, shutdown and reset, and safety protection. Each module contained clear scoring points and deduction items in order to improve the consistency and discriminative power of assessment [12].

This modular design not only enabled teachers to quickly judge whether students had completed each operation in a standardized manner, but also helped students understand in which steps they were likely to lose points, so that targeted improvement could be made in subsequent experiments.

3.3 Data Collection and Feedback Method

Considering that experimental-course evaluation is frequent and involves multiple participants, complete reliance on paper forms would lead to a high data-processing burden. Therefore, this study adopted “Wenjuanxing + Excel” to build a lightweight data-processing scheme. Students completed self-evaluation and peer evaluation by scanning a QR code on their mobile phones, while teachers entered observation records and operation scores into Excel templates after class. Preset formulas then automatically completed data cleaning, weighted calculation, and chart generation.

Although this method has a relatively low technical threshold, it is highly practical in actual teaching. Teachers do not need to develop additional complex systems, and students can obtain stage-based feedback more quickly, such as individual competence radar charts and weakness prompts, thereby enhancing the timeliness and usability of evaluation.

4. Implementation Process of Evaluation Based on the 5E Model

To truly integrate evaluation into the teaching process, this study embedded evaluation activities into the complete teaching chain of “pre-class preparation - in-class exploration - post-class reflection”, thus forming an implementation process corresponding to the 5E teaching model (see Table 4).

In the pre-class stage, students engaged with instructional materials, preview tasks, and problem situations, with teachers examining their preparation and understanding-corresponding to the dimension of “interest and participation.” During class, students performed operations, observations, and discussions while teachers recorded their

performance in instrument use, judgment, analysis, and teamwork-covering “exploration and operation,” “explanation and understanding,” and “collaboration and communication.” After

class, students submitted reports and completed reflective self-evaluations, mainly addressing “extension and innovation” and “reflection and improvement.”

Table 4. Implementation Flow of Evaluation based on the 5E Model

Phase	5E Teaching Phase	Core Teaching Activities	Embedded Evaluation Activity Design	Evaluation Subjects
Pre-class	E1 Engagement	Watch operational micro-lectures; review relevant literature	Pre-class self-test; submit self-assessment form on preview	Students (self-evaluation)
In-class	E2 Exploration	Group hands-on operation; explore unknown sample structure	Teacher’s behaviorally anchored observation record; peer evaluation among group members	Teacher, Peers
In-class	E3 Explanation	Inter-group data comparison; in-depth teacher explanation of principles	Assessment of spectrum/data analysis ability; classroom Q&A evaluation	Teacher
In-class	E4 Elaboration	Experimental design; extended application	Report quality review; peer evaluation during defense	Teacher, Peers
Post-class internalization	E5 Evaluation	Write data analysis report; reflect on the experiment	Standardized experiment report grading; self-reflection scale	Teacher, Students

For the final course grade, this study replaced the traditional fragmented scoring with a two-level nested structure: “process-oriented comprehensive evaluation (Sp) as the main body, with summative criterion-referenced assessment as a threshold” [13,14]. Specifically:

(1) Process-oriented comprehensive evaluation (Sp, 70% of final grade)

This was calculated strictly according to the weighted six dimensions described in Section 1.3. Within Sp, data sources were integrated via the mapping matrix in Table 3: teacher observation records accounted for 60%, student self-evaluation 20%, and peer evaluation 20%. This component spanned the whole process.

(2) Summative criterion-referenced assessment (30% of final grade)

This included a standardized practical operation exam (20%) and a computer-based theoretical test (10%). A minimum requirement was set: if the summative total was below 60, the student would fail regardless of Sp score, ensuring basic mastery of safety norms and core principles.

Thus, the final grade (Total) was calculated as:

$$\text{Total} = 0.7 \times \text{Sp} + 0.2 \times \text{Oexam} + 0.1 \times \text{Texam}$$

where Oexam and Texam are the practical and theoretical test scores (out of 100). The Sp formula is given in Section 1.3.

To prevent evaluation from remaining mere “scoring,” the course also provided immediate, weekly, mid-term, and final feedback. Based on recorded results, teachers gave group feedback for common issues and individualized guidance

for specific problems, transforming evaluation outcomes into a foundation for future learning.

5. Teaching Practice and Effect Analysis

5.1 Participants, Research Design, and Performance Outcomes

The study was conducted at the College of Chemistry and Materials Science, Jinan University. The experimental group comprised 58 students from the 2025 cohort majoring in Materials Science and Engineering, who adopted the 5E teaching model combined with the multiple evaluation system [15]. A historical control group of 55 students from the 2024 cohort of the same major used the traditional “lab report + attendance” approach. The two groups were comparable in course content, teaching staff, and hardware conditions. After teaching, operational and theoretical test scores were compared between the two groups, and a satisfaction questionnaire was distributed to the experimental group, yielding 56 valid responses. As shown in Table 5, the experimental group's excellence rate in the independent operation assessment reached 86.2%, which was 18.6 percentage points higher than the control group. The average theoretical test score increased by 7.2 points, and the comprehensive course excellence rate rose from 40.6% to 62.1%, an increase of 21.5 percentage points in the longitudinal comparison. Classroom observation and student feedback further revealed that earlier

evaluation prompted students to pay more attention to pre-class preparation, operational details, and parameter-setting rationale, while the number of students "only watching others" decreased. The introduction of standardized

operational scoring sheets specifically heightened students' awareness of instrument specifications and safety requirements, which may have been a key factor driving the improvement in practical scores.

Table 5. Comparison of Core Achievement Indicators between the Experimental Group and the Control Group (%)

Group	N	Average Score of Operation Assessment	Average Score of Theoretical Test	Average Comprehensive Score	Excellence Rate (%)
Control group	55	81.4	78.6	80.2	21.8
Experimental group	58	89.1	85.8	87.4	43.3

5.2 Learning Engagement and Student Satisfaction

Beyond academic performance, classroom behavior and subjective feedback also improved. Classroom sampling showed that the proportion of students actively raising exploratory questions

(e.g., on parameter setting and abnormal spectra) rose from about 20% to 45%. Peer-evaluation scores for group discussion participation remained stable at 4.2/5, and previously less engaged students showed improvement in task undertaking and communication.

Table 6. Distribution of Student Satisfaction with the Multiple Evaluation System in the Experimental Group (N = 56)

Survey Item	Very satisfied (%)	Relatively satisfied (%)	Neutral (%)	Dissatisfied (%)
Clarity of evaluation criteria	41.4	46.6	12.0	0
Timeliness of process feedback	37.9	48.3	13.8	0
Helps improve class participation	39.7	44.8	15.5	0
Helps improve standardization of experimental operations	44.8	43.1	12.1	0
Overall satisfaction	43.1	44.8	12.1	0

Questionnaire results (Table 6) were positive: 96.4% found the rubric helpful for clarifying operational requirements, and 94.6% considered the indicators clear, reducing grade uncertainty. Open-ended responses noted that the process-oriented evaluation encouraged timely self-summary after each experiment, unlike report-only scoring.

Overall, the evaluation reform not only changed grade structure but also reshaped student participation in the lab course, which is practically significant for a course that emphasizes standardized operation and immediate judgment.

6. Conclusion

Focusing on the problems of single evaluation, insufficient process attention, and delayed feedback in Materials Analysis and Characterization Experiments, this study built a multiple evaluation system based on the 5E model, with six first-level and 24 second-level indicators, and developed supporting scales for teacher observation, student self-evaluation, peer evaluation, and operational skills. Teaching practice showed that embedding evaluation into the whole process improved students'

operational standardization, participation, and reflection, with final performance better than that of the traditional mode.

However, limitations exist. A longitudinal historical comparison design was used without a contemporaneous randomized control; the sample was limited to one college and major; the implementation period was short, requiring further verification of long-term effects; and self-/peer evaluations may still be subjective. Future work will introduce ANCOVA to isolate the net effect of the reform, and may combine learning analytics and intelligent text analysis to enhance refinement.

Overall, this system achieves a relatively complete process-oriented evaluation and feedback mechanism without relying on complex platforms, offering reference value for similar laboratory course reforms.

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