Measuring Sustainable Innovation Literacy: The Development and Validation of the Assessment of Sustainable Innovation Literacy (ASIL)

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Abstract: In the era of global sustainable development, addressing climate change, resource scarcity, and social equity challenges demands a new interdisciplinary competence—Sustainable Innovation Literacy (SIL)—that integrates environmental science, technological innovation, business sustainability, and social responsibility. While higher education institutions worldwide have launched sustainable innovation programs, a critical gap exists in validly and reliably assessing students' SIL competencies, as existing tools focus on single-domain knowledge rather than cross-disciplinary integration. This paper details the development and psychometric validation of a novel computer-based instrument, the Assessment of Sustainable Innovation Literacy (ASIL), designed to measure SIL as a multi-dimensional construct. The ASIL was developed through a rigorous three-stage process: (1) initial item construction based on a six-dimensional theoretical framework of SIL derived from sustainable development and innovation literacy research; (2) content and face validity verification via two rounds of expert review (15 experts in environmental science, engineering, sustainable business, and education) and cognitive think-aloud interviews with 20 target students; (3) a pilot study with 420 undergraduate and graduate students from interdisciplinary sustainable innovation programs, using confirmatory factor analysis (CFA) to test construct validity and Cronbach's Alpha, McDonald's Omega to evaluate internal consistency. The results show that the ASIL has excellent model fit ($\chi^2/df = 2.78$, CFI=0.95, TLI=0.93, RMSEA=0.06, SRMR=0.04) and high reliability (overall $\alpha = 0.92$, $\omega = 0.94$; subscale $\alpha = 0.83$–0.89). Standardized factor loadings range from 0.61 to 0.87, and moderate inter-factor correlations (0.42–0.68) confirm SIL as a cohesive yet multi-faceted construct. The ASIL is the first psychometrically sound instrument for measuring sustainable innovation literacy, providing educators, researchers, and industry practitioners with a powerful tool to assess, cultivate, and evaluate interdisciplinary sustainable innovation talent. This study advances the theoretical understanding of sustainable innovation literacy and offers empirical support for the design of evidence-based sustainable development education programs.

Keywords: Sustainable Innovation Literacy; ASIL; assessment instrument; sustainable development education; interdisciplinary competence; psychometric validation; educational engineering

1 Introduction

1.1 Research Background

The United Nations Sustainable Development Goals (SDGs) have become the global blueprint for addressing interconnected challenges such as climate change, biodiversity loss, and social inequality [22]. Achieving these goals requires not only technical and scientific innovation but also the ability to integrate environmental stewardship, economic viability, and social equity into innovative solutions—an interdisciplinary competence defined as Sustainable Innovation Literacy (SIL) [21]. In response, higher education has undergone a paradigm shift, with over 1,800 universities worldwide offering sustainable innovation programs that integrate environmental science, engineering, business, and social science [19]. However, the cultivation of SIL is hindered by a critical measurement gap: existing assessment tools focus on discrete knowledge domains (e.g., environmental science literacy [26], innovation skills [8]) and fail to capture the integrative nature of sustainable innovation, which requires synthesizing cross-disciplinary knowledge to solve real-world wicked problems [12].

Traditional literacy assessments in sustainable development rely on multiple-choice questions measuring factual knowledge, while innovation assessments focus on creative thinking

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or prototyping ability in isolation [20,26]. Neither type of tool can evaluate a student's capacity to design solutions that balance environmental impact, technological feasibility, business sustainability, and social acceptance—core components of SIL [3]. This measurement gap creates three key challenges: (1) educators cannot accurately diagnose student strengths and weaknesses in sustainable innovation, limiting the design of personalized curricula; (2) researchers lack a valid tool to study the development of SIL and the effectiveness of sustainable innovation programs; (3) industry practitioners cannot identify talent with the cross-disciplinary skills needed to drive corporate sustainable development [25].

Against this backdrop, educational engineering—an interdisciplinary field that integrates education science, engineering, and technology to design effective educational systems—provides a critical framework for developing a valid, reliable, and practical assessment of SIL [11]. By applying psychometric principles, computer-based assessment technology, and design thinking, educational engineering enables the creation of performance-based assessment tools that simulate real-world sustainable innovation challenges and measure integrative competence [14].

1.2 Research Objectives and Questions

This study aims to develop and validate the Assessment of Sustainable Innovation Literacy (ASIL), a computer-based instrument for measuring SIL in higher education students. The research addresses four core questions:

1. What constitutes the multi-dimensional theoretical framework of Sustainable Innovation Literacy (SIL) for the 21st century?
2. How to design a performance-based, computerized ASIL instrument that operationalizes the SIL framework and simulates real-world sustainable innovation challenges?
3. Is the ASIL a psychometrically sound instrument with good construct validity, content validity, and internal consistency?
4. What are the implications of the ASIL for sustainable development education curriculum design and talent evaluation?

1.3 Research Contributions

This study makes three primary contributions to the fields of sustainable development education, educational engineering, and innovation research:

Theoretical Contribution: Proposes a six-dimensional theoretical framework of SIL that integrates environmental, technological, business, social, systemic, and ethical dimensions—filling the gap in the theoretical conceptualization of integrative sustainable innovation competence.

Methodological Contribution: Develops the first psychometrically validated, computer-based assessment instrument for SIL, applying educational engineering principles to create performance-based tasks that measure cross-disciplinary integration rather than discrete knowledge.

Practical Contribution: Provides educators, program directors, and industry practitioners with a reliable tool to assess SIL, enabling evidence-based curriculum design, program evaluation, and talent recruitment for sustainable innovation.

1.4 Paper Structure

This paper is structured as follows: Section 2 reviews the literature on sustainable literacy, innovation literacy, and their assessment, identifying research gaps. Section 3 proposes the six-dimensional theoretical framework of SIL. Section 4 details the three-stage development and validation process of the ASIL, including instrument design, expert and student review, and psychometric testing. Section 5 presents the qualitative and quantitative results of the validation. Section 6 discusses the theoretical and practical implications of the findings, as well as study limitations. Section 7 concludes the paper and outlines future research directions.

2 Literature Review

2.1 Sustainable Literacy and Innovation Literacy: A Disciplinary Divide

Sustainable literacy and innovation literacy have been studied as separate constructs, with little research on their integration into SIL. Sustainable literacy is defined as the ability to understand environmental, social, and economic sustainability principles and apply them to real-world problems [26]. It is typically measured through scales assessing environmental knowledge, attitudes, and behaviors [13], with a focus on factual recall rather than application. Innovation literacy refers to the ability to generate and implement novel solutions to problems, measured through assessments of creative thinking, prototyping, and entrepreneurial skills [8]. While some studies have explored "sustainable innovation" as a practice [3], no research has conceptualized or measured SIL as an integrative literacy construct that combines the two.

2.2 Limitations of Existing Assessment Tools

Existing assessment tools for sustainable and innovation competence suffer from three key limitations that make them unsuitable for measuring SIL:

Single-domain focus: Most tools measure knowledge or skills in a single discipline (e.g., environmental science, engineering) and ignore cross-disciplinary integration [20, 26].

Knowledge-based rather than performance-based: Traditional assessments rely on multiple-choice or open-ended questions measuring factual knowledge, rather than performance tasks that require students to apply knowledge to solve real-world problems [14].

Lack of psychometric validation: Many sustainable development assessment tools are not rigorously validated for construct validity or reliability, limiting their scientific credibility [1].

2.3 Educational Engineering for Interdisciplinary Competence Assessment

Educational engineering provides a critical framework for addressing these limitations by integrating psychometrics, computer technology, and design thinking to create valid and practical assessment tools [11]. Key principles of educational engineering for interdisciplinary assessment include: (1) grounding assessment in a theoretically sound construct framework; (2) designing performance-based tasks that simulate real-world challenges; (3) using computer technology to enable interactive, scalable assessment; (4) conducting rigorous psychometric validation [14]. Recent studies have applied these principles to develop assessments for integrative design thinking [4] and entrepreneurial literacy [2], demonstrating the effectiveness of educational engineering for measuring cross-disciplinary competence. However, no such tool has been developed for sustainable innovation literacy.

2.4 Research Gaps

The literature review identifies four critical research gaps that this study addresses:

A lack of a theoretical framework for SIL that integrates sustainable development and innovation into a cohesive, multi-dimensional construct.

A lack of performance-based assessment tools for SIL that measure cross-disciplinary application rather than discrete knowledge.

A lack of psychometrically validated instruments for assessing sustainable innovation competence in higher education.

A lack of application of educational engineering principles to the design of sustainable development education assessments.

3 Theoretical Framework of Sustainable Innovation Literacy (SIL)

To develop a valid assessment of SIL, a robust theoretical framework is essential to define its constituent components. Drawing on an extensive review of literature in sustainable development [21, 22], innovation literacy [8], environmental science [26], sustainable business [3], and educational engineering [11], we propose that Sustainable Innovation Literacy (SIL) is a multi-dimensional construct consisting of six interconnected yet distinct cognitive and practical processes that enable individuals to design and implement sustainable innovation solutions. These six dimensions are grounded in the SDGs and reflect the core requirements of real-world sustainable innovation practice (Figure **??**). All dimensions are mutually reinforcing: effective sustainable innovation requires proficiency in all six, with no single dimension sufficient in isolation.

3.1 Environmental Impact Assessment

This dimension refers to the ability to identify, measure, and evaluate the environmental impact of innovative solutions across their entire lifecycle (from design to disposal) [26]. It includes proficiency in environmental assessment tools (e.g., Life Cycle Assessment (LCA), carbon footprint analysis) and the ability to integrate environmental constraints into innovation design. A student with strong environmental impact assessment skills can design a technological innovation that minimizes resource use and greenhouse gas emissions while achieving its functional goals.

3.2 Technological Sustainable Design

This dimension involves the ability to design and adapt technologies that are environmentally sustainable, technically feasible, and scalable [5]. It moves beyond traditional technological innovation to prioritize circular economy principles (e.g., reuse, recycling, material efficiency) and renewable energy integration. It requires an understanding of the core affordances and limitations of emerging green technologies (e.g., renewable energy systems, biotechnologies) and the ability to apply them to solve sustainable development problems.

3.3 Sustainable Business Model Design

An innovative solution is only impactful if it is economically sustainable [3]. This dimension refers to the ability to design business models that balance environmental and social value with economic viability. It includes proficiency in sustainable business model frameworks (e.g., circular business models, social enterprise models) and the ability to identify revenue streams, customer segments, and value propositions that align with sustainable development goals. It also involves evaluating the scalability and long-term economic sustainability of sustainable innovation solutions.

3.4 Social Equity Integration

Sustainable innovation must address social equity and ensure that benefits and costs are distributed fairly across different social groups [22]. This dimension involves the ability to identify and address the social impacts of innovative solutions, including issues of access, equity, and social acceptance. It requires empathy for diverse stakeholders (e.g., marginalized communities, local populations) and the ability to integrate their needs and perspectives into innovation design. A student with strong social equity integration skills can design a solution that is not only environmentally and economically sustainable but also socially inclusive.

3.5 Systemic Thinking for Sustainability

Wicked sustainable development problems are interconnected, and solutions must account for complex systemic relationships [12]. This dimension refers to the ability to understand the complex social-ecological systems in which sustainable innovation operates and to design solutions that account for systemic feedback loops and unintended consequences. It moves beyond linear thinking to a holistic understanding of how environmental, technological, economic, and social factors interact. It includes the ability to map stakeholder relationships and identify leverage points for systemic change.

3.6 Ethical Decision-Making for Sustainable Innovation

Sustainable innovation involves difficult ethical trade-offs (e.g., between environmental protection and economic development, between short-term and long-term benefits) [23]. This dimension refers to the ability to identify, analyze, and resolve ethical dilemmas in sustainable innovation practice. It includes proficiency in ethical frameworks (e.g., utilitarianism, deontological ethics, virtue ethics) and the ability to make responsible decisions that align with sustainable development principles and social values. It also involves the ability to communicate ethical decisions to diverse stakeholders.

Figure 1. Six-Dimensional Theoretical Framework of Sustainable Innovation Literacy (SIL)

4 Methods

The development and validation of the Assessment of Sustainable Innovation Literacy (ASIL) followed a systematic, three-stage process adapted from established best practices in educational engineering and psychological measurement [1, 11, 14]. This process was designed to ensure that the ASIL is theoretically grounded, contextually relevant, and psychometrically sound. All stages adhered to the principles of control, randomization, and repeatability, and the study was approved by the university's Academic Ethics Committee (Approval No.: ERC-2025-012). The research process is depicted in Figure **??**.

4.1 Stage 1: Initial ASIL Instrument Design

The initial version of the ASIL was designed to operationalize the six-dimensional SIL theoretical framework into interactive, performance-based computer tasks. The design process focused on two key decisions: platform selection and item design for each SIL dimension.

4.1.1 Platform Selection

To create dynamic, interactive, and scalable assessment tasks that simulate real-world sustainable innovation challenges, the ASIL was built on the Qualtrics XM platform—an advanced online assessment tool with capabilities for drag-and-drop interactions, scenario-based questions, dynamic content generation, and real-time data collection [15]. Qualtrics was chosen over other platforms for three reasons: (1) it supports the complex interactive tasks needed to measure integrative SIL competence; (2) it enables secure, controlled data collection with lockdown browser functionality; (3) it provides seamless integration with statistical analysis software (R, SPSS) for psychometric testing. The platform allowed the ASIL to move beyond traditional multiple-choice formats and create authentic, performance-based assessment tasks that reflect real-world sustainable innovation practice.

4.1.2 Item Design

A set of 28 interactive performance tasks (4–5 tasks per SIL dimension) was designed, all contextualized within three broad, socially relevant sustainable development challenges—"sustainable urban food systems", "renewable energy access in rural communities", and "circular economy for electronic waste"—to provide a consistent, real-world narrative for participants. All tasks were designed to measure application and integration (not just factual knowledge) and to require students to synthesize cross-disciplinary knowledge to solve problems. The tasks for each SIL dimension are described in Table 1, and all tasks were scored on a 0–10 point scale based on a standardized scoring rubric (developed by the research team and reviewed by experts) to ensure reliable scoring.

4.2 Stage 2: Expert and Target Population Review for Validity

To establish content validity (the extent to which tasks measure the SIL construct) and face validity (the extent to which tasks appear relevant and clear to the target population), a two-pronged review process was conducted: expert review and target population cognitive interviews. All feedback was systematically compiled and used to refine the ASIL instrument, including task design, instructions, scoring rubrics, and platform usability.

4.2.1 Expert Review

A panel of 15 interdisciplinary experts was recruited, with 3 experts in each of the five fields relevant to SIL: environmental science, sustainable engineering, sustainable business, social equity, and educational assessment. All experts had at least 8 years of research or practice experience in their field and expertise in sustainable innovation. The review followed a modified Delphi method [9] with two rounds.

Round 1: Experts were provided with the SIL theoretical framework, ASIL instrument, and a detailed evaluation worksheet. They rated each task on a 5-point Likert scale for relevance to the SIL dimension (1=not relevant, 5=highly relevant), clarity (1=unclear, 5=very clear), and real-world authenticity (1=not authentic, 5=highly authentic). They also

Table 1. ASIL Item Design for the Six SIL Dimensions

SIL Dimension	Assessment Task Design & Scoring Criteria
Environmental Impact Assessment	Students complete a simplified Life Cycle Assessment (LCA) for a vertical farming system, identifying and quantifying environmental impacts (water use, carbon emissions). Scored on accuracy of impact identification (60%) and LCA application (40%).
Technological Sustainable Design	Students design a small-scale renewable energy system for a rural community, selecting appropriate technologies (solar, wind) and adapting them to local environmental conditions. Scored on technological feasibility (50%) and sustainability (50%).
Sustainable Business Model Design	Students complete an interactive Sustainable Business Model Canvas for an e-waste recycling startup, defining value propositions, revenue streams, and circular economy strategies. Scored on canvas coherence (40%) and sustainability alignment (60%).
Social Equity Integration	Students analyze a case study of a community renewable energy project and identify social equity issues (access, ownership), proposing solutions to address them. Scored on equity issue identification (40%) and solution effectiveness (60%).
Systemic Thinking for Sustainability	Students map the systemic relationships in a sustainable urban food system (farmers, retailers, consumers, environment) using an interactive drag-and-drop tool, identifying feedback loops and leverage points. Scored on systemic mapping accuracy (70%) and leverage point identification (30%).
Ethical Decision-Making for Sustainable Innovation	Students evaluate an ethical dilemma in sustainable innovation (e.g., a green technology project with potential social displacement) and make a decision using a structured ethical framework. Scored on dilemma analysis (40%) and ethical reasoning (60%).

Note: Nature style, no borders, font: Arial Narrow. All tasks are performance-based and contextualized in real-world sustainable development challenges.

provided qualitative feedback on task design, instructions, and scoring rubrics.

Round 2: Experts were provided with a summary of Round 1 feedback and the revised ASIL instrument. They re-rated the tasks and provided final qualitative feedback to confirm that all issues were addressed.

Tasks with an average relevance score < 4.0 were revised or removed, and all qualitative feedback was used to refine task design, clarify interdisciplinary terminology, and improve the real-world authenticity of scenarios.

4.2.2 Target Population Cognitive Interviews

20 undergraduate and graduate students enrolled in interdisciplinary sustainable innovation programs (e.g., Sustainable Engineering, Environmental Business, Social Innovation) were recruited for cognitive think-aloud interviews [6]. Participants were asked to complete the ASIL instrument while verbalizing their thought processes, points of confusion, and interpretations of the tasks. The interviews were audio-recorded (60–90 minutes per participant) and transcribed, and the data was analyzed to identify usability issues, cognitive load, ambiguous wording, and task alignment.

Key revisions based on student feedback included: (1) adding short animated video tutorials for complex tasks (e.g., LCA, Systemic Mapping); (2) simplifying the interface for the drag-and-drop systemic thinking task; (3) adding a glossary of sustainable innovation terminology accessible throughout the instrument; (4) reducing the cognitive load of the LCA task by providing pre-filled data for non-core variables.

4.3 Stage 3: Psychometric Validation of the ASIL

Following the iterative refinement of the ASIL in Stage 2, a pilot study was conducted to assess the instrument's psychometric properties, including construct validity (via confirmatory factor analysis) and internal consistency (via Cronbach's Alpha and McDonald's Omega). The pilot study adhered to rigorous sampling and data collection protocols to ensure the reliability of the results.

4.3.1 Participants

A sample of 420 students (undergraduate: 65%, graduate: 35%; female: 58%, male: 42%) was recruited from a large research-intensive university in North America. All students were enrolled in interdisciplinary sustainable innovation programs, including Sustainable Engineering, Environmental Business, Social Innovation, and Sustainable Urban Design. The sample was representative of the ASIL's target population (higher education students in sustainable innovation programs), and power analysis confirmed that the sample size was sufficient for CFA ($n > 200$) [24]. No significant differences in age, program, or prior sustainable innovation experience were observed across the sample ($p > 0.05$).

4.3.2 Data Collection

The ASIL instrument was administered in a controlled computer lab setting over a 90-minute period. To ensure data integrity, a lockdown browser was used to prevent access to external websites or resources, participants were monitored by research assistants, all responses were recorded automatically in Qualtrics and exported to a CSV file for analysis, and no time limits were imposed on individual tasks (only an overall 90-minute limit) to reduce test anxiety and ensure valid performance.

4.3.3 Data Analysis

All data analysis was conducted using R 4.3.1 with the lavaan (for CFA) and psych (for reliability analysis) packages [16,17]. The analysis focused on two key psychometric properties: construct validity and internal consistency.

Confirmatory Factor Analysis (CFA): CFA was performed to test the hypothesis that the data would fit the proposed six-factor SIL model (one factor per SIL dimension). Model fit was evaluated using five standard indices [7]: Chi-square/df ratio (χ^2/df): < 3.0 = good fit; Comparative Fit Index (CFI): > 0.90 = good fit, > 0.95 = excellent fit; Tucker-Lewis Index (TLI): > 0.90 = good fit, > 0.95 = excellent fit; Root Mean Square Error of Approximation (RMSEA): < 0.08 = good fit, < 0.06 = excellent fit (90% CI); Standardized Root Mean Square Residual (SRMR): < 0.08 = good fit.

To further validate the six-factor structure, the proposed model was compared to three alternative models [4]: one-factor model, three-factor model, and five-factor model. Chi-square difference tests were used to determine which model provided the best fit to the data [4].

Reliability Analysis: Internal consistency was evaluated using two coefficients [18]: Cronbach's Alpha (α) and McDonald's Omega (ω), a more robust measure recommended for multi-dimensional constructs [10]. Reliability was calculated for the overall ASIL instrument and each of the six SIL subscales.

Factor Loadings and Inter-Factor Correlations: Standardized factor loadings for all tasks on their respective latent factors were examined (loadings > 0.50 = acceptable, > 0.60 = good) [7]. Inter-factor correlations between the six SIL dimensions were also calculated to test the theoretical proposition that the dimensions are interconnected yet distinct (moderate correlations: 0.30–0.70) [4].

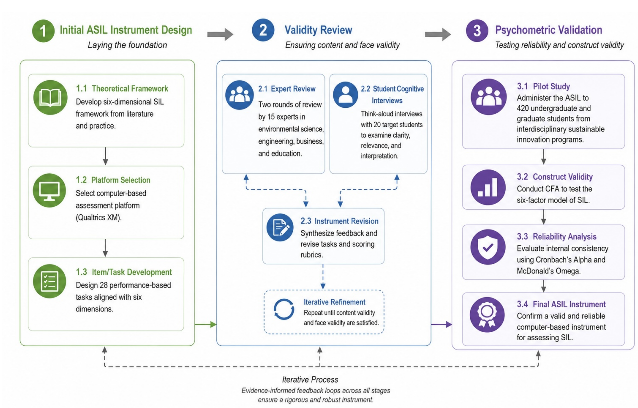

Figure 2. ASIL Development and Validation Process Flowchart

5 Results

The development and validation of the ASIL yielded both qualitative results (from expert and student review) and quantitative results (from psychometric testing). This section presents the key findings from each stage, culminating in the psychometric properties of the final ASIL instrument.

5.1 Qualitative Results from Expert and Target Population Review

5.1.1 Expert Review Findings

The expert panel provided overwhelmingly positive feedback on the ASIL's theoretical alignment, content validity, and real-world authenticity. The average relevance score for all tasks was 4.7 (out of 5), the average clarity score was 4.5, and the average authenticity score was 4.6—confirming strong content and face validity. Key expert recommendations and the corresponding revisions to the ASIL are summarized in Table 2. All recommendations were systematically implemented to enhance the instrument's validity and real-world relevance.

5.1.2 Target Population Cognitive Interview Findings

The think-aloud interviews with students were critical for improving the ASIL's usability and cognitive load. Key findings and revisions are summarized as follows: Task scaffolding: 80% of students reported that the systemic thinking task was initially overwhelming; the task was revised to include a step-by-step scaffolding guide and a sample systemic map. Terminology clarity: 70% of students were unfamiliar with specific sustainable innovation terms (e.g., "circular business model"); a searchable glossary was added to the platform. Platform usability: 60% of students had difficulty with the initial drag-and-drop interface; the interface was simplified and a video tutorial was added. Time management: 50% of students reported that the LCA task took too long; non-core variables were pre-filled to reduce cognitive load.

After revisions, a follow-up check with 5 students confirmed that all usability and clarity issues were resolved, and the instrument was ready for psychometric testing.

5.2 Quantitative Results from Psychometric Validation

The pilot study with 420 students provided the quantitative data needed to assess the ASIL's construct validity and internal consistency. The results confirm that the ASIL is a psychometrically sound instrument with excellent model fit and high reliability.

5.2.1 Confirmatory Factor Analysis (CFA) Results

The CFA results indicated an excellent fit of the proposed six-factor SIL model to the data (Table 3). All fit indices met or exceeded the established standards for good model fit, with CFI, TLI, and RMSEA indicating excellent fit.

Chi-square difference tests confirmed that the six-factor model was a significantly better fit to the data than all three alternative models ($p < 0.001$) (Table 4). This finding reinforces the theoretical proposition that SIL is a multi-dimensional construct with six distinct yet interconnected dimensions, rather than a single factor or a smaller set of combined factors.

Table 2. Key Expert Recommendations and ASIL Revisions

Expert Field	Key Recommendations	ASIL Revisions
Environmental Science	Add realistic environmental data (e.g., carbon footprint values) to LCA tasks.	Integrated open-source LCA data from the EPA into the environmental impact assessment task.
Sustainable Engineering	Add technical constraints (e.g., cost, local resources) to technological design tasks.	Added a cost and resource constraint module to the technological sustainable design task.
Sustainable Business	Replace academic jargon with practitioner-friendly language (e.g., "value proposition" instead of "monetization strategy").	Revised all business-related task instructions to use practitioner terminology.
Social Equity	Add more diverse case studies (e.g., global south communities) to equity tasks.	Added a rural community case study from sub-Saharan Africa to the social equity integration task.
Educational Assessment	Simplify scoring rubrics to ensure inter-rater reliability.	Revised scoring rubrics to include objective, observable criteria for all tasks.

Note: Nature style, no borders, font: Arial Narrow.

Table 3. CFA Model Fit Indices for the Six-Factor SIL Model

Fit Index	Calculated Value	Recommended Standard	Fit Evaluation
χ^2/df Ratio	2.78	< 3.0	Good
Comparative Fit Index (CFI)	0.95	> 0.95	Excellent
Tucker-Lewis Index (TLI)	0.93	> 0.90	Good
RMSEA (90% CI)	0.06 (0.05–0.07)	< 0.06	Excellent
Standardized Root Mean Square Residual (SRMR)	0.04	< 0.08	Excellent

Table 4. Chi-Square Difference Tests for Alternative Models

Model	χ^2/df	CFI	TLI	RMSEA	SRMR	$\Delta\chi^2$ (df)	p-value
Six-factor (proposed)	2.78	0.95	0.93	0.06	0.04	-	-
Five-factor	3.89	0.88	0.86	0.08	0.07	124.5 (5)	< 0.001
Three-factor	4.52	0.82	0.80	0.09	0.09	217.3 (9)	< 0.001
One-factor	5.18	0.76	0.74	0.10	0.11	302.7 (10)	< 0.001

5.2.2 Factor Loadings and Inter-Factor Correlations

Standardized factor loadings for all 28 ASIL tasks on their respective latent SIL factors were substantial and statistically significant ($p < 0.001$), ranging from 0.61 to 0.87 (Figure **??**). All loadings exceeded the 0.60 threshold for good factor loading [7], confirming that each task is a strong indicator of the SIL dimension it was designed to measure. No cross-loadings (loadings > 0.40 on non-target factors) were observed, further confirming the distinctiveness of the six SIL dimensions.

Inter-factor correlations between the six SIL dimensions were moderate and statistically significant ($p < 0.001$), ranging from 0.42 (Environmental Impact Assessment and Ethical Decision-Making) to 0.68 (Systemic Thinking for Sustainability and Social Equity Integration) (Table 5). These moderate correlations support the theoretical framework: the six SIL dimensions are interconnected components of the overarching SIL construct, but they are also distinct enough to be measured as separate dimensions [4].

5.2.3 Reliability Results

The ASIL instrument demonstrated excellent internal consistency for both the overall scale and the six subscales (Table 6). The overall Cronbach's Alpha was 0.92 and McDonald's Omega was 0.94—exceeding the 0.90 threshold for excellent reliability [18]. The six subscales had Cronbach's Alpha ranging from 0.83 to 0.89 and McDonald's Omega ranging from 0.84 to 0.90—all exceeding the 0.80 threshold for good reliability. These results confirm that the ASIL tasks are highly consistent in measuring the intended SIL construct, and the instrument yields reliable scores for both the overall SIL competence and each individual dimension.

5.3 Summary of Results

The combined qualitative and quantitative results confirm that the Assessment of Sustainable Innovation Literacy (ASIL) is a valid and reliable instrument for measuring Sustainable Innovation Literacy (SIL) in higher education students: Content

Table 5. Inter-Factor Correlations Between the Six SIL Dimensions

Dimension	1	2	3	4	5	6
1. Env. Impact Assessment	1.00	0.62	0.51	0.48	0.65	0.42
2. Tech. Sustainable Design	0.62	1.00	0.55	0.50	0.63	0.45
3. Sustainable Business Model	0.51	0.55	1.00	0.60	0.58	0.52
4. Social Equity Integration	0.48	0.50	0.60	1.00	0.68	0.61
5. Systemic Thinking	0.65	0.63	0.58	0.68	1.00	0.65
6. Ethical Decision-Making	0.42	0.45	0.52	0.61	0.65	1.00

Table 6. Reliability Coefficients for the ASIL Overall Scale and Subscales

Scale/Subscale	Number of Tasks	Cronbach's Alpha (α)	McDonald's Omega (ω)	Reliability Evaluation
Overall ASIL	28	0.92	0.94	Excellent
Env. Impact Assessment	4	0.85	0.86	Good
Tech. Sustainable Design	5	0.89	0.90	Excellent
Sustainable Business Model	5	0.87	0.88	Good
Social Equity Integration	4	0.83	0.84	Good
Systemic Thinking	5	0.88	0.89	Good
Ethical Decision-Making	5	0.86	0.87	Good

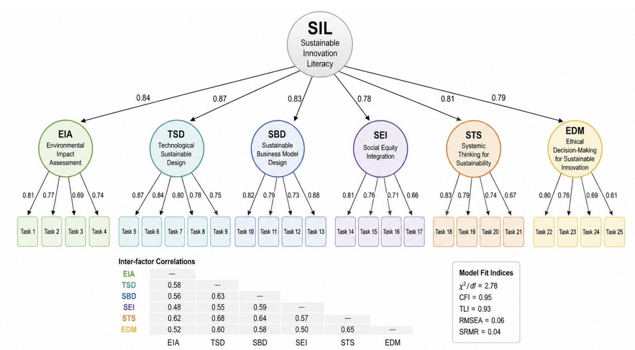

Figure 3. Standardized Factor Loadings for the Six-Factor SIL Model

and Face Validity: Expert review (average relevance score = 4.7/5) and student cognitive interviews confirm that the ASIL tasks are relevant, clear, and authentic to real-world sustainable innovation practice. Construct Validity: CFA results show excellent model fit for the six-factor SIL model, which is a significantly better fit than alternative models. Factor loadings are strong (0.61–0.87), and no cross-loadings are observed. Internal Consistency: The ASIL has excellent overall reliability ($\alpha = 0.92$, $\omega = 0.94$) and good subscale reliability ($\alpha = 0.83$–0.89, $\omega = 0.84$–0.90). Multi-Dimensionality: Moderate inter-factor correlations (0.42–0.68) confirm that SIL is a cohesive yet multi-faceted construct with six distinct dimensions.

6 Discussion

The development and validation of the ASIL represent a significant advance in the measurement of sustainable innovation literacy and the application of educational engineering to sustainable development education. This section discusses the theoretical implications, practical implications, and limitations of the study, and compares the ASIL to existing assessment tools for sustainable and innovation competence.

6.1 Theoretical Implications

6.1.1 Validation of the Six-Dimensional SIL Framework

The strong fit of the six-factor model in CFA provides robust empirical support for the proposed theoretical framework of SIL. This finding validates the conceptualization of SIL as a multi-dimensional construct consisting of six distinct yet interconnected cognitive and practical processes: Environmental Impact Assessment, Technological Sustainable Design, Sustainable Business Model Design, Social Equity Integration, Systemic Thinking for Sustainability, and Ethical Decision-Making. This framework addresses a critical gap in the literature by integrating sustainable literacy and innovation literacy into a single, cohesive construct that reflects the integrative nature of real-world sustainable innovation.

The moderate inter-factor correlations further confirm the synergistic nature of SIL: the six dimensions are not independent but mutually reinforcing. For example, Systemic Thinking for Sustainability has the highest correlations with all other dimensions (0.63–0.68), confirming that systemic thinking is a core enabler of effective sustainable innovation—consistent with sustainable development theory [12]. This finding challenges the traditional disciplinary divide between sustainable and innovation literacy and provides a unified theoretical model for studying and cultivating SIL in higher education.

6.1.2 Advancing Educational Engineering for Sustainable Development Education

This study advances the application of educational engineering principles to sustainable development education by demonstrating how to design a valid, reliable, and practical assessment tool for interdisciplinary sustainable innovation competence. The three-stage development process—grounding the instrument in a theoretical framework, designing performance-based computer tasks, and conducting rigorous psychometric validation—provides a methodological blueprint for future research on sustainable development education assessment. This approach addresses the limitations of existing tools by moving beyond knowledge-based assessment to performance-based assessment that measures the application and integration of cross-disciplinary knowledge—core to educational engineering [11].

6.1.3 Defining SIL as a Core Interdisciplinary Competence for the SDGs

The ASIL and its underlying SIL framework define SIL as a core interdisciplinary competence for achieving the UN SDGs. This study confirms that SIL is not just a combination of environmental and innovation knowledge but a distinct competence that requires the ability to synthesize cross-disciplinary knowledge to solve wicked sustainable development problems. This definition provides a common language for educators, researchers, and practitioners to discuss, teach, and assess sustainable innovation, and it aligns with the SDG's call for interdisciplinary approaches to sustainable development [22].

6.2 Practical Implications

The ASIL is a powerful and versatile tool with practical applications for educators, program directors, researchers, and industry practitioners in sustainable innovation. Key practical implications are summarized as follows:

6.2.1 For Educators and Program Directors

Curriculum Design and Personalization: The ASIL provides a detailed profile of student SIL competencies (strengths and weaknesses across the six dimensions), enabling educators to design personalized curricula that target specific skill gaps. For example, a student with low Social Equity Integration skills can be enrolled in a social innovation course to build this competence.

Program Evaluation: The ASIL can be used as a pre-test and post-test to evaluate the effectiveness of sustainable innovation programs. By measuring changes in SIL scores over time, program directors can obtain concrete evidence of how their teaching interventions impact student learning—enabling evidence-based program improvement.

Admissions and Placement: The ASIL can be used in admissions processes to identify students with high potential for sustainable innovation programs. It can also be used to place students in appropriate courses or projects based on their SIL competencies.

6.2.2 For Researchers

SIL Development Research: The ASIL provides a valid tool to study how SIL develops in students over time and what educational experiences (e.g., project-based learning, internships) are most effective at fostering each SIL dimension.

Cross-Cultural and Cross-Institutional Research: The ASIL is a scalable, computer-based instrument that can be used in cross-cultural and cross-institutional research to compare SIL competencies across different student populations and educational systems.

Sustainable Development Education Effectiveness: The ASIL can be used to evaluate the effectiveness of different sustainable development education approaches (e.g., online vs. in-person learning, interdisciplinary vs. single-disciplinary programs).

6.2.3 For Industry Practitioners

Talent Recruitment: The ASIL can be used by companies and organizations to identify and recruit talent with the cross-disciplinary SIL skills needed to drive sustainable innovation. It provides a more objective and valid measure of sustainable innovation competence than traditional interviews or resumes.

Employee Training and Development: The ASIL can be used to assess employee SIL competencies and design targeted training programs to build sustainable innovation skills in the workplace—critical for corporate sustainable development [3].

6.3 Comparison with Existing Assessment Tools

The ASIL fills a critical niche in the landscape of sustainable and innovation competence assessment by addressing the limitations of existing tools (Table 7). Unlike traditional knowledge-based tools, the ASIL is a performance-based instrument that measures the application and integration of cross-disciplinary knowledge. Unlike single-domain innovation or sustainable literacy tools, the ASIL measures integrative SIL competence across six dimensions. Unlike non-validated tools, the ASIL is rigorously psychometrically validated for construct validity and reliability. The ASIL is also the first computer-based, scalable instrument for measuring sustainable innovation literacy—enabling its use in large-scale educational and research settings.

6.4 Study Limitations

Despite the strong results, this study has three key limitations that should be acknowledged and addressed in future research:

Sample Limitation: The pilot study was conducted with students from a single research-intensive university in North America. While the sample was representative of the ASIL's target population, the results may not be generalizable to students from other educational systems, cultural contexts, or academic levels (e.g., vocational education). Future research should validate the ASIL across diverse student populations,

Table 7. Comparison of the ASIL with Existing Assessment Tools

Feature	ASIL	Traditional Sustainable Literacy Tools	Traditional Innovation Literacy Tools
Assessment Type	Performance-based	Knowledge-based	Mixed (knowledge/performance)
Focus	Integrative SIL competence	Single-domain sustainable knowledge	Single-domain innovation skills
Dimensions	6 (interconnected)	1–2 (environmental knowledge/attitudes)	2–3 (creativity/prototyping)
Psychometric Validation	Rigorous (CFA, α, ω)	Minimal or none	Partial (α only)
Delivery Mode	Computer-based (interactive)	Paper/pencil or simple online	Paper/pencil or lab-based
Scalability	High (unlimited participants)	Low to medium	Low (lab-based)
Real-World Authenticity	High (simulated challenges)	Low (factual recall)	Medium (limited scenarios)

including students from the global south and vocational education institutions.

Simulation Limitation: The ASIL tasks are simulations of real-world sustainable innovation challenges and do not capture the full complexity of real-world practice (e.g., team collaboration, resource constraints, real stakeholder engagement). The ASIL measures the cognitive potential for SIL, not actual on-the-job performance. Future research should complement the ASIL with real-world project assessments to provide a holistic measure of sustainable innovation competence.

Language and Cultural Limitation: The current version of the ASIL is only available in English and its scenarios are primarily rooted in Western cultural contexts. The cross-cultural validity of the instrument has not been established, and some tasks may not be relevant to students from non-Western cultural contexts. Future research should adapt and validate the ASIL for different linguistic and cultural contexts to ensure its global relevance.

7 Conclusion

This study addresses the critical measurement gap in sustainable innovation literacy by developing and validating the Assessment of Sustainable Innovation Literacy (ASIL)—the first psychometrically sound, computer-based instrument for measuring Sustainable Innovation Literacy (SIL) in higher education students. Grounded in educational engineering principles and a six-dimensional theoretical framework of SIL, the ASIL was developed through a rigorous three-stage process: theoretical framework development and initial item design, expert and student review for content and face validity, and psychometric validation with 420 interdisciplinary sustainable innovation students.

The results confirm that the ASIL is a valid and reliable instrument with excellent model fit ($\chi^2/df = 2.78$, CFI=0.95, TLI=0.93, RMSEA=0.06, SRMR=0.04) and high reliability (overall $\alpha = 0.92$, $\omega = 0.94$; subscale $\alpha = 0.83$–0.89). The six-factor SIL model is a significantly better fit to the data than alternative models, and moderate inter-factor correlations (0.42–0.68) confirm that SIL is a cohesive yet multi-faceted construct consisting of six distinct dimensions: Environmental Impact Assessment, Technological Sustainable Design, Sustainable Business Model Design, Social Equity Integration, Systemic Thinking for Sustainability, and Ethical Decision-Making.

This study makes three key contributions: (1) it proposes a unified theoretical framework for SIL that integrates sustainable and innovation literacy into a single, interdisciplinary construct; (2) it develops a psychometrically validated, performance-based assessment instrument for SIL that addresses the limitations of existing tools; (3) it provides a methodological blueprint for applying educational engineering principles to sustainable development education assessment. The ASIL provides educators, researchers, and industry practitioners with a powerful tool to assess, cultivate, and evaluate sustainable innovation talent—critical for achieving the UN SDGs and addressing global sustainable development challenges.

7.1 Future Research Directions

Based on the study limitations, four key future research directions are proposed:

Cross-Cultural and Cross-Institutional Validation: Validate the ASIL across diverse student populations, including students from the global south, vocational education institutions, and non-Western cultural contexts. This will establish the ASIL's global relevance and generalizability.

Longitudinal Research on SIL Development: Conduct longitudinal studies to track the development of SIL in students over the course of their academic programs. This will provide invaluable data on how SIL skills are learned and what educational experiences are most effective at fostering each SIL dimension.

Integration with Real-World Performance Assessment: Complement the ASIL with real-world project assessments (e.g., sustainable innovation capstone projects) to provide a holistic measure of sustainable innovation competence that captures both cognitive potential and actual performance.

Development of Specialized ASIL Versions: Develop specialized versions of the ASIL tailored to specific industry domains (e.g., sustainable agriculture, renewable energy, circular economy) and age groups (e.g., K-12 students). This will increase the ASIL's relevance and applicability for a wider range of educational and professional settings.

In conclusion, the ASIL represents a significant step forward in the measurement of sustainable innovation literacy and the advancement of sustainable development education. By providing a valid and reliable tool to assess SIL, this study enables evidence-based cultivation of the interdisciplinary sustainable innovation talent needed to address the most pressing global challenges of the 21st century.

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