Developing of the sustainability competencies instrument for pre-service biology teachers

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| ARTICLE INFO	ABSTRACT
	This study constructs and validates an instrument for evaluating sustainability competencies in higher education, particularly within the context of education for sustainable development. The instrument assesses knowledge, attitudes, and values critical for tackling sustainability challenges. The creation involved expert evaluations and a comprehensive survey of 644 pre-service biology teachers in Indonesia. The analysis employed exploratory factor analysis and confirmatory factor analysis, leading to the identification of seven essential competency dimensions: systems thinking competency, anticipatory competency, normative competency, strategic competency, collaboration competency, self-awareness competency, and problem-solving competency. The analysis categorized these into two primary factors: social competence and collaboration, and critical thinking and sustainable action. The instrument demonstrated reliability and construct validity, evidenced by a Cronbach's alpha value of 0.88, indicating its robustness. This instrument is a valuable resource for incorporating sustainability competencies into higher education programs and curricula. Future research should implement this in diverse educational settings and integrate qualitative methods to enhance the understanding of sustainability competency development. **Keywords:** sustainability competencies, instrument validation, pre-service biology teachers

INTRODUCTION

Environmental crises driven by rapid urbanization, population growth, and technological and industrial expansion continue to intensify; demanding urgent global attention (Şeker, 2023). Issues such as global warming, climate change, and unmanaged waste significantly threaten human well-being; while industrial activities, transportation systems, and livestock farming contribute substantially to greenhouse gas emissions that accelerate global temperature rise (Widiyawati, 2020). Simultaneously, increased population pressure and inadequate waste management lead to the deterioration of water quality, biodiversity loss, and ecosystem degradation (França et al., 2019; Rajak, 2021). These interconnected crises underscore the need for societal competencies capable of supporting sustainable decision-making and transformative action.

Education has a strategic role in cultivating such competencies by deepening understanding of biodiversity, promoting value-based reflection, and encouraging lifelong learning (Mardiansyah Purmadi et al., 2020; Moyer-Horner et al., 2010). UNESCO (2017) outlines eight sustainability competencies—such as systemic thinking, anticipatory thinking, and collaboration—that are essential for addressing complex environmental challenges (Dlouhá et al., 2019). However, higher education institutions often struggle to integrate these competencies effectively due to the limited contextualization of teaching practices and insufficient educator preparation (Cörvers et al., 2016; Tejedor et al., 2019). Consequently, there is a growing need for structured, measurable approaches to ensure that students acquire the competencies necessary for responding to sustainability challenges.

The development of sustainability competency instruments becomes critical because such tools allow educators to measure baseline student abilities, design learning experiences aligned with competency needs, and embed sustainability more systematically into curricula (Redman et al., 2021). Accurate measurement also fosters the development of social skills, problem-solving strategies (Almulla & Al-Rahmi, 2023), preparedness for eco-social challenges (Murphy, 2023), and the capacity for conscious action in environmental crises (Pokhrel, 2021). Moreover, robust assessment supports students' readiness to engage with and contribute to achieving the sustainable development goals
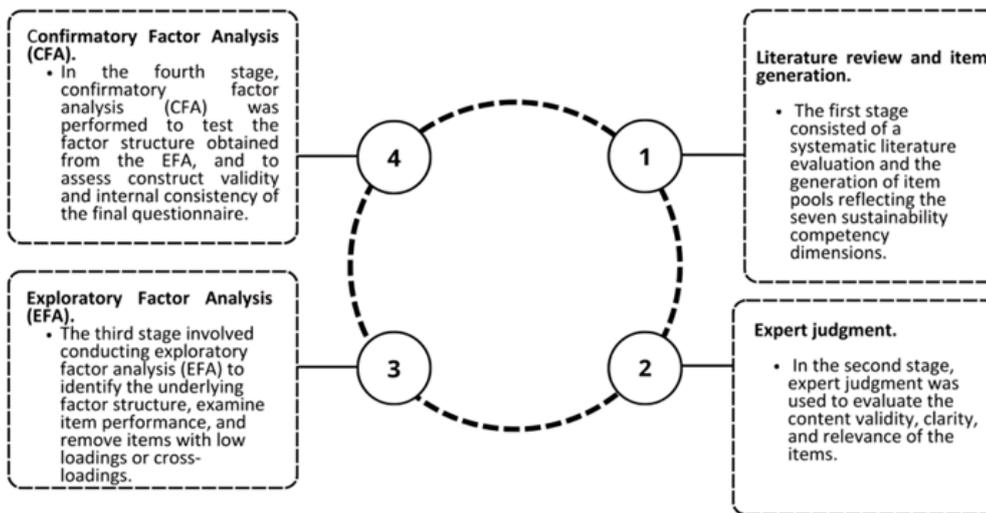
Figure 1. Research stages (Adapted from Grougiou, 2024; Ledesma et al., 2024; Marenus et al., 2023; Valderrama-Hernández et al., 2025)

(SDGs) (Vasconcelos et al., 2022). Well-developed instruments can also help map sustainability gaps, strengthen community university linkages, and advance best practices for SDG attainment (Handayani et al., 2024; Zikargae et al., 2022). By integrating knowledge, attitudes, and values; these instruments help cultivate responsible citizens capable of producing innovative solutions and contributing to social and environmental well-being (Bertel et al., 2022; Sarid & Goldman, 2021).

Despite its importance, research on sustainability competency assessment instruments remains limited. Existing studies note ambiguities in instrument scales, constraints in sample diversity, and the scarcity of cross-disciplinary validation (Annelin & Bostrom, 2023; Waltner et al., 2019). While Zhang et al. (2025) developed a reliable triple bottom line-based CO-SS ($\alpha = 0.917$) for higher education, this advancement still leaves open the need for more integrated validation across disciplines. Similarly, Toma et al. (2024) designed a GreenComp-based instrument for elementary students, but its scope was restricted by sample size and age range. Collectively, these studies reveal a clear research gap: the absence of comprehensive, integrated, and cross-disciplinary validated instruments particularly for assessing sustainability competencies in higher education contexts. Without valid and reliable instruments, the risk of measurement bias increases significantly, undermining the accuracy of research findings and the effectiveness of educational interventions. Therefore, rigorous examination of research instruments prior to their application is essential to ensure accuracy, consistency, and fairness.

Given these gaps, developing a sustainability competency assessment instrument grounded in an established competency framework is both timely and necessary. This study is designed to address two primary research questions:

1. How valid and reliable is the instrument developed to measure sustainability competencies among pre-service biology teachers?

2. What is the impact of confirmatory and exploratory factor analysis (EFA) results on the dimensions of sustainability competencies?

The findings are expected to contribute to the advancement of education for sustainable development (ESD) by offering a validated instrument that supports curriculum design, learning strategies, and assessment practices for future biology teachers.

MATERIALS AND METHOD

Research Design

The proposed evaluation instrument for sustainability competencies is conceptualized as a test. The design followed a four-phase process, beginning with a systematic literature review and the development of assessment items informed by established sustainability frameworks (Grougiou, 2024; Stropoli et al., 2019). In the second phase, expert judgment was employed to validate content relevance and theoretical alignment; thereby, reinforcing the instrument's construct validity and reliability (Loureiro et al., 2024; Valderrama-Hernández et al., 2025). The third phase involved conducting EFA to identify the underlying factor structure of the instrument. EFA serves as a data reduction technique that reveals latent constructs by examining patterns of collinearity among variables (Jusoh et al., 2022; Ledesma et al., 2024; Watson, 2017). This phase is essential for clarifying the dimensionality of the instrument and establishing a preliminary measurement model (Zakaria et al., 2024). The fourth phase consisted of evaluating the construct validity and internal consistency of the refined questionnaire through confirmatory factor analysis (CFA). CFA is used to assess the degree to which the empirical data fit the hypothesized factor structure derived from the EFA, thereby confirming the validity of the measurement model and ensuring reliable assessment of the intended constructs, typically supported by internal consistency indices such as Cronbach's alpha (Inci & Bakan, 2022; Marenus et al., 2023; Seydi et al., 2021; Silva et al., 2021) (**Figure 1**).

Research Sample

According to methodological recommendations, factor analysis requires a minimum of five to ten respondents per item, or at least 300 participants for stable factor extraction (Rouquette & Falissard, 2011; Siddiqui, 2013). With 644 respondents, this study substantially exceeds the minimum sample threshold, ensuring robust statistical power for both EFA and CFA analyses. This study involved 644 biology education students from multiple universities in Indonesia. These students were drawn from multiple provinces, including Central Java, East Java, West Java, Riau, East Nusa Tenggara, Pekanbaru, West Papua, Jambi, North Maluku, Maluku, and other regions within Eastern Indonesia. The dataset was segmented into two groups for analysis: 120 participants were allocated for EFA, while 338 participants were designated for CFA. The total number of respondents exceeded the minimum threshold for factor analysis procedures as recommended in previous studies (Schreiber, 2021; Shrestha, 2021). The extensive geographic representation enhances the generalizability of the instrument designed to assess sustainability competencies within biology education.

Data Collection

The data for this study were collected through an online survey administered via Google Forms from May 2024 to July 2024. The data collection process was conducted in collaboration with lecturers from biology education programs at multiple universities in Indonesia. Participating lecturers assisted in distributing the survey link to students within their respective institutions through internal academic communication channels. This nationwide collaboration enabled broad participation from students representing diverse geographic and institutional backgrounds, thereby supporting the representativeness and coverage of the dataset in assessing sustainability competencies in biology education.

Procedure

The evaluation of content validity and data reduction involved an analysis of student responses to the test-based instrument designed to measure sustainability competencies. Mean (M) and standard deviation (SD) were computed for each item to examine the distribution patterns of scores. Total item correlations were evaluated using the Pearson product-moment correlation coefficient to assess the consistency and relevance of each item in relation to the overall test structure. EFA was performed to confirm that the instrument measured coherent and interpretable constructs, facilitating the reduction of overlapping or ambiguous items through the identification of underlying latent factors. EFA facilitated the identification of item groupings that represented distinct dimensions of sustainability competencies. CFA was performed to assess the model's robustness and construct validity (Baharum et al., 2023).

CFA was employed to validate the structural framework of the test-based instrument aimed at assessing sustainability competencies. The analysis validated the factor structure established during the exploratory phase and delineated the overarching domains represented by the final test items. The maximum likelihood estimation method was used, employing the covariance matrix to assess the fit of the proposed measurement model to the observed data (Zhang & Spall, 2025; Zhou et al., 2022). Model fit was evaluated through various recognized goodness-of-fit indices: Chi-square divided by degrees of freedom (x^2/df), Tucker-Lewis index (TLI), goodness-of-fit index (GFI), adjusted goodness-of-fit index (AGFI), standardized root mean square residual (SRMR), and comparative fit index (CFI). A model is considered a good fit when the criteria are met: x^2/df ≤ 3.00, root mean square error of approximation (RMSEA) ≤ 0.08, and SRMR ≤ 0.10 (du Plessis & Kirsten, 2025; Stefana et al., 2024). Values near or above 0.90 for GFI, AGFI, CFI, and TLI provide additional evidence of the model's adequacy (Baharum., 2023). The RMSEA is a widely used fit index in structural equation modeling that measures how well a model, with optimally chosen parameter estimates, fits the population covariance matrix (Jobst et al., 2021). RMSEA values ≤ 0.05 represent a close fit, while values ≤ 0.08 indicate an acceptable fit (Lai & Green, 2016; McNeish et al., 2018). The internal consistency of the test items was evaluated using Cronbach's alpha, composite reliability (CR), and average variance extracted (AVE), in conjunction with structural fit assessments. These metrics guarantee that the test items within each domain reliably assess the same underlying construct. Cronbach's alpha values were interpreted following George and Mallery (2024): α ≥ 0.9 (excellent), α ≥ 0.8 (good), α ≥ 0.7 (acceptable), α ≥ 0.6 (questionable), and α ≤ 0.5 (poor). Acceptable values were defined as CR ≥ 0.70, and AVE ≥ 0.50, indicating a reliable and consistent assessment tool for evaluating sustainability competencies.

RESULTS

The research findings are presented in alignment with the four stages:

(1) the literature evaluation and the creation of the items,

(2) expert judgment was required,

(3) EFA, or EFA, and

(4) evaluating the construct validity and internal consistency of the resulting questionnaire through CFA.

First Step

This step includes a literature review to formulate the concept of sustainable competencies in the context of education. Sustainable competencies are understood as a combination of knowledge, skills, values, attitudes, and willingness to act effectively in support of sustainable development. These competencies consist of seven main dimensions. First, systems thinking competence (STC) encompasses the ability to understand the interconnections between components in social, environmental, and economic systems (Frey et al., 2025; Green et al., 2021; Karaarslan Semiz & Teksoz, 2020; Reynolds et al., 2017). Systems thinking is crucial for implementing SDGs as it facilitates better conversation and cooperation between various stakeholders and helps in understanding complex relationships. It is also a core competency in ESD, enabling learners to solve sustainability-related problems by understanding the dynamic interactions within systems. Second, anticipatory competence

Table 1. Results of expert validation of the sustainability competencies test

No	Aspect evaluated	Expert 1	Expert 2	Expert 3	Average percentage (%)	Validity category
1	Alignment of indicators with the construct	5	4	4	86.7	Highly valid
2	Clarity of indicator wording	4	3	4	73.3	Fairly valid
3	Relevance to learning objectives	5	5	4	93.3	Highly valid
4	Readability and visual layout (face validity)	3	4	3	66.7	Fairly valid
5	Clarity of language	4	5	4	86.7	Highly valid
6	Coherence among items within the same dimension	4	3	4	73.3	Fairly valid
7	Completeness of content coverage	5	4	3	80.0	Highly valid
	Average percentage (%)	85.7	80.0	74.3	80.0	Highly valid

Table 2. Expert suggestions, comments, and revisions

No	Expert suggestions and comments	Revision action
1	Indicators appropriately represent the dimensions of sustainability competencies. Consider adding local context for better relevance	Added locally relevant case examples and terminology to reflect sustainability issues in local Indonesian contexts
2	Simplify sentence structures in some items to enhance readability for students.	Revised complex sentence structures into shorter, clearer sentences. Removed redundant phrases.
3	Suggested improving layout aesthetics and consistency in numbering and spacing	Reformatted layout: standardized spacing, numbering system, and section headings.
4	Language is generally clear. Avoid technical terms without providing definitions	Replaced technical terms with simpler alternatives or added brief definitions in parentheses where needed.
5	Indicators within each dimension are coherent. Recommend clarifying dimension boundaries to avoid overlap	Reviewed and refined definitions and boundaries of each competency dimension to reduce overlap and improve clarity.
6	All major competencies are covered. Suggest adding one self-reflection indicator under the normative dimension	Added a new item under the normative dimension focusing on ethical self-reflection and values clarification.

(AC) refers to the ability to project future scenarios and develop strategies based on these projections. This competence is crucial in various fields; including driving, where it allows individuals to predict future traffic situations and respond accordingly, enhancing safety and efficiency (Stahl et al., 2013, 2014). In the context of sustainability, AC involves engaging with multiple futures, managing uncertainty, and steering towards a sustainable path. This competence is essential for developing long-term foresight and resilience in urban planning and other domains (Gardiner & Rieckmann, 2015; Solobutina, 2015). Scenario-based learning is a practical approach to developing AC, as it involves real-world problems that foster decision-making and solution-finding processes (Souza et al., 2022).

Third, normative competence (NC) refers to the understanding and application of sustainability values and principles (Mach & Ebersberger, 2024). Fourth, strategic competence (SC) involves planning and implementing concrete actions to achieve sustainability goals (Mach & Ebersberger, 2024; Mulder, 2017; Singer Brodowski et al., 2025). Fifth, collaboration competence emphasizes the ability to work together across disciplines and cultures, which is crucial for addressing complex sustainability challenges. This competence is essential for integrating diverse perspectives and knowledge, fostering cross-disciplinary cooperation, and enhancing the effectiveness of sustainability initiatives (Dalla Valle, 2021; Laursen & Bennyson, 2024; Vesterinen & Ratinen, 2024). Sixth, Self-awareness competence highlights the importance of understanding one's personal values and influence in sustainability practices. This competence involves critical self-reflection, empathy, and the ability to recognize and manage one's emotions and motivations (Costa & Cipolla, 2025; Zarzycki, 2025). Self-awareness is crucial for ethical reasoning and leadership development, as it helps individuals navigate complex sustainability challenges and make informed decisions (Nissen, 2025). Moreover, self-awareness in the context of environmental performance can prevent overconfidence and ensure continuous improvement in sustainability efforts (Lähdeaho & Vilko, 2022). Seventh, problem-solving competence reflects the ability to address sustainability challenges through innovative and applicable solutions. This competence is essential for navigating the complex, real-world issues associated with sustainable development, requiring a multidisciplinary approach that integrates knowledge from various fields such as engineering, natural sciences, and social sciences (Hart et al., 2015; Zilahy & Zsoka, 2020). Problem-solving competence in sustainability involves a combination of creativity, critical thinking, collaboration, and adaptability. Educational institutions play a crucial role in developing these competencies through innovative and interdisciplinary approaches (Birdman & Lang, 2025; Haim & Aschauer, 2024; Hansen & Bertel, 2023; Haritas & Harini, 2025; Risopoulos et al., 2020). These seven dimensions form the basis for the development of a sustainability competency measurement instrument.

Second Step

The sustainability competency assessment instrument in this study was subjected to an expert validation process to assess its content and face validity. Face validity is the degree to which the evaluation's organization, structure, sequence, and format are logical and functional (**Table 1**). The experts' approval rate averages 80%, categorizing it as highly valid. All items received a score of 3 or higher, indicating expert approval of the instrument's form and content.

Experts offered recommendations and feedback for enhancing the developed sustainability competencies test (**Table 2**).

Table 3. KMO and Bartlett's test of sphericity

Test	Value
KMO	0.696
Bartlett's test of sphericity	
Approximate Chi-square	1,687.490
df	210
Significance	0.000

Table 4. Results of descriptive statistical analysis

Item	M	SD
STC1	3.5917	.70408
STC2	3.5417	.67233
STC3	3.5750	.69406
AC1	3.3833	.84200
AC2	3.6417	.78640
AC3	3.4833	.74454
NC1	3.4917	.74468
NC2	3.3167	.54976
NC3	3.2833	.74680
SC1	3.4417	.79701
SC2	3.4250	.80610
SC3	3.4167	.78412
CC1	3.3417	.55754
CC2	3.3500	.51286
CC3	3.4000	.54077
SAC1	3.3167	.54976
SAC2	3.2667	.51422
SAC3	3.3000	.57394
PSC1	3.6250	.73407
PSC2	3.2500	.58338
PSC3	3.4583	.65972

Table 5. Construct, item, and correlation with total

Construct	Item	Correlation with total	Description
STC	STC1	0.928	Valid
	STC2	0.906	Valid
	STC3	0.825	Valid
AC	AC1	0.770	Valid
	AC2	0.858	Valid
	AC3	0.847	Valid
NC	NC1	0.838	Valid
	NC2	0.720	Valid
	NC3	0.810	Valid
SC	SC1	0.986	Valid
	SC2	0.977	Valid
	SC3	0.993	Valid
CC	CC1	0.759	Valid
	CC2	0.810	Valid
	CC3	0.698	Valid

Third Step

EFA was used to test the construct validity of the research instrument. Before performing EFA, the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (MSA) and Bartlett's test of sphericity were conducted to verify the suitability of the data for factor analysis (**Table 3**). Based on the results of EFA using the principal component analysis (PCA) method, the KMO value of 0.696 indicates an adequate level of sample suitability for factor analysis. This value is above the minimum threshold of 0.60, so the data is considered sufficient for factor extraction. Additionally, the result of Bartlett's test of

Table 6. Construct, item, Cronbach's alpha coefficient for each item and average alpha

Construct	Item	CA	AA
STC	STC 1, STC 2, STC 3	0.825, 0.827, 0.824	0.825
AC	AC 1, AC 2, AC 3	0.821, 0.823, 0.814	0.819
NC	NC 1, NC 2, NC 3	0.819, 0.818, 0.824	0.820
SC	SC 1, SC 2, SC 3	0.809, 0.809, 0.808	0.809
CC	CC 1, CC 2, CC 3	0.823, 0.822, 0.827	0.824
SAC	SAC 1, SAC 2, SAC 3	0.822, 0.819, 0.820	0.820
PSC	PSC 1, PSC 2, PSC 3	0.816, 0.823, 0.829	0.823

Note. CA: Cronbach's alpha coefficient for each item & AA: Average alpha

Table 7. Final EFA results for 21 items (n = 120)

Dimension	Components						
	1	2	3	4	5	6	7
STC 1			0.926				
STC 2			0.919				
STC 3			0.773				
AC 1				0.681			
AC 2				0.893			
AC 3				0.807			
NC 1					0.774		
NC 2					0.708		
NC 3					0.801		
SC 1	0.950						
SC 2	0.943						
SC 3	0.952						
CC 1							0.688
CC 2							0.813
CC 3							0.680
SAC 1		0.927					
SAC 2		0.935					
SAC 3		0.858					
PSC 1						0.672	
PSC 2						0.822	
PSC 3						0.785	

sphericity shows a significance value of 0.000, indicating that there is sufficient correlation among the variables to form a factor structure that can be further analyzed.

The descriptive analysis results, presented in **Table 4**, indicate that the M scores for each item varied from 3.26 to 3.64, with SD ranging from 0.51 to 0.80. The values were utilized to evaluate if the items demonstrated comparable variability and contributed uniformly to the overall scale score.

Based on the results of the correlation analysis between each item and the total construct score, the correlation values obtained indicate that all items in each construct have adequate validity (**Table 5**).

The results of the reliability analysis using Cronbach's Alpha values per item show that all constructs in this study demonstrate fairly good internal consistency (**Table 6**).

The EFA results identified seven indicators (**Table 7**), each of which in the research instrument shows a tendency to load predominantly on one factor component.

The results of total variance explained (**Table 8**) show that there are seven main components with eigenvalues greater than 1, in accordance with Kaiser's criteria.

Table 8. Total variance explained

Component	Initial Eigenvalues	% variance	% cumulative	Rotation sums of squared loadings	% variance	% cumulative
1	5.003	23.823	23.823	2.924	13.924	13.924
2	2.777	13.223	37.046	2.619	12.470	26.394
3	2.310	11.000	48.046	2.419	11.520	37.914
4	1.691	8.052	56.098	2.199	10.474	48.387
5	1.557	7.415	63.513	1.953	9.301	57.689
6	1.356	6.459	69.972	1.939	9.234	66.923
7	1.166	5.552	75.523	1.806	8.601	75.523
8-21	< 1.0	< 5%	< 80%	-	-	-

Table 9. Dimension of SC

No	D	Description	Indicators
1	STC	Ability to recognize, understand, and analyze relationships between components in a system, including interactions between social, environmental, and economic systems	**STC1.** Ability to analyze interactions and relationships in environmental and social systems. **STC2.** Identify long-term impacts and consequences of actions or decisions. **STC3.** Apply a holistic approach to identify the causes and solutions of complex problems.
2	AC	Ability to forecast and evaluate possible outcomes of different actions over the long term	**AC1.** Identify potential future trends and scenarios. **AC2.** Evaluate the risks and potential impacts of various scenarios on sustainability. **AC3.** Create strategic planning based on scenario analysis.
3	NC	Ability to understand and create values, principles, and goals related to sustainability	**NC1.** Identify values and principles that support social and environmental sustainability. **NC2.** Evaluate actions and policies based on sustainability values. **NC3.** Think critically about existing norms and values and consider sustainable alternatives.
4	SC	Ability to design and implement effective actions towards sustainability goals	**SC1.** Identify concrete steps to achieve sustainability goals. **SC2.** Establish effective priorities in strategic planning for sustainability. **SC3.** Implement the sustainability plan by considering available resources.
5	CC	Ability to work effectively in teams and collaboration across sectors, cultures, and disciplines	**CC1.** Communicate effectively with individuals from different backgrounds. **CC2.** Build mutually beneficial relationships to achieve sustainability goals. **CC3.** Able to negotiate and reach consensus in collaborative situations.
6	SAC	Ability to recognize and understand the role, values, and influence of individuals in supporting sustainability	**SAC1.** Identify strengths, weaknesses, and personal values related to sustainability. **SAC2.** Identify the impact of personal behavior on environmental and social sustainability. **SAC3.** Develop the ability to reflect on practices that support sustainability.
7	PSC	Ability to solve complex problems related to sustainability, including skills to identify, formulate, and solve problems in innovative ways	**PSC1.** Identify sustainability issues and devise steps to solve them. **PSC2.** Using innovative thinking in finding solutions to complex problems. **PSC3.** Apply sustainability knowledge in practical contexts and real cases.

Note. D: Dimension

Table 10. CFA results

|	Estimated model
Chi-square	603.660
Number of model parameters	63.000
Number of observations	338.000
df	168.000
p	0.000
χ^2/df	3.593
RMSEA	0.088
RMSEA low 90% confidence interval	0.080
RMSEA high 90% confidence interval	0.095
GFI	0.864
AGFI	0.814
PGFI	0.629
SRMR	0.066
NFI	0.905
TLI	0.911
CFI	0.929
AIC	729.660
BIC	970.512

A total of 21 EFA result items with seven dimensions (**Table 9**) were subsequently analyzed using CFA.

Fourth Step

The CFA results also show that the seven dimensions using the correlation model meet the suitability requirements (**Table 10** and **Figure 2**).

Chi-square value shows significant results (statistically unfit), other fit indicators such as RMSEA, SRMR, GFI, AGFI, NFI, TLI, and CFI indicate that this model has a good to fairly good level of fit with the data used. Therefore, this model is acceptable and suitable for further interpretation. The Parsimony goodness of fit index (PGFI), Akaike information criterion (AIC), and Bayesian information criterion (BIC) were included to assess model parsimony. Lower AIC and BIC values indicate a better-fitting and more parsimonious model, while PGFI assesses the balance between model fit and complexity (Bader & Moshagen, 2022; Jung et al., 2025).

The researchers assessed internal consistency to evaluate the measuring scale's effectiveness across different respondents. Each dimension was assessed utilizing two distinct metrics: AVE and CR (**Table 11**).
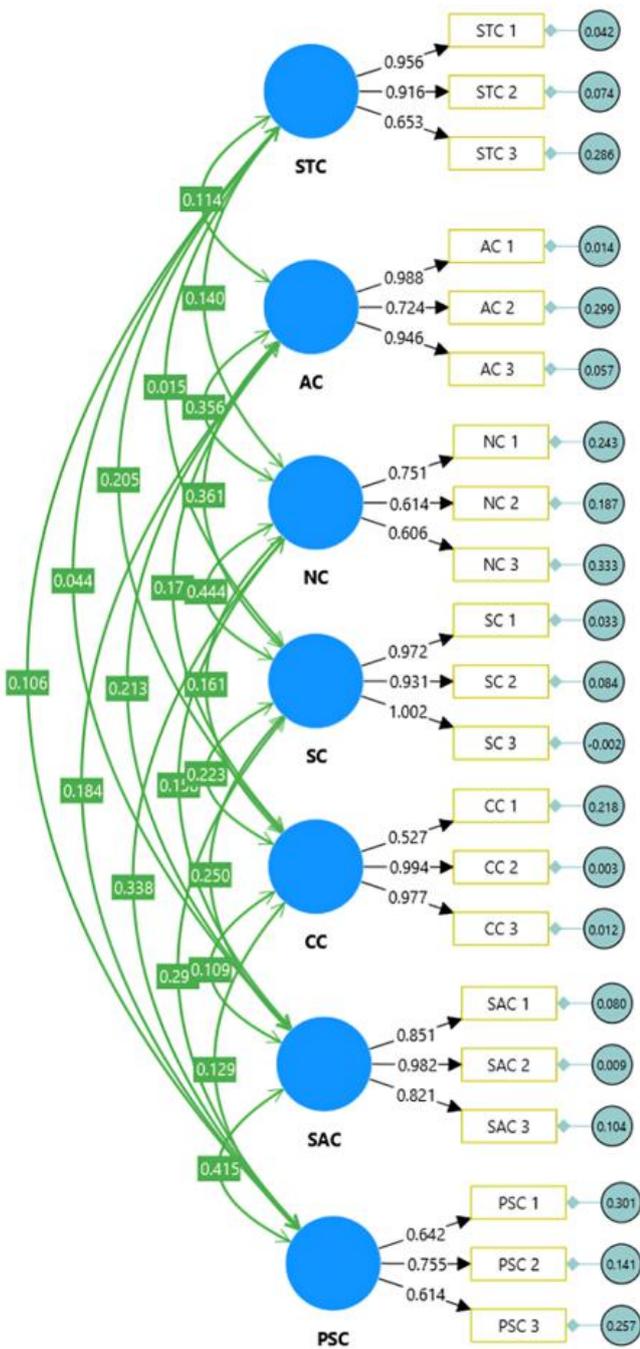
Figure 2. CFA with the correlated model (n = 338) (Adapted from Ringle et al., 2024)

Table 11. AVE and CR

Domain/item	AVE	CR
AC	0.798	0.92
CC	0.774	0.92
NC	0.537	0.735
PSC	0.553	0.761
SAC	0.788	0.914
SC	0.939	0.981
STC	0.727	0.889

The calculations of AVE and CR for each domain/item in the model indicate that all domains/items satisfy the criteria for convergent validity and item reliability.

Table 12. Correlation of the seven dimensions of sustainability competencies

	AC	CC	NC	PSC	SAC	SC	STC
AC 1	0.988						
AC 2	0.724						
AC 3	0.946						
CC 1		0.527					
CC 2		0.994					
CC 3		0.977					
NC 1			0.751				
NC 2			0.614				
NC 3			0.606				
PSC 1				0.642			
PSC 2				0.755			
PSC 3				0.614			
SAC 1					0.851		
SAC 2					0.982		
SAC 3					0.821		
SC 1						0.972	
SC 2						0.931	
SC 3						1.000	
STC 1							0.956
STC 2							0.916
STC 3							0.653

The researchers also analyzed the relationships between the dimensions/items that were formed and established in this study (**Table 12**). Based on the analysis results, each item exhibits a large to very large positive correlation with its respective competency dimension, reflecting strong internal consistency and stable inter-item associations. This pattern of correlations confirms that the items within each construct are theoretically coherent and empirically convergent, thereby reinforcing the convergent validity of the sustainability competency instrument developed in this study.

DISCUSSION

The development of the sustainability competency instrument in this study aims to identify the key competencies required by students to address sustainability challenges and to provide a robust tool for supporting ESD. The analysis demonstrates that the seven theoretically derived dimensions; STC, AC, NC, SC, collaborative competence (CC), self-awareness competency (SAC), and problem-solving competency (PSC) are empirically valid and reliable. At the same time, the EFA reveals a more parsimonious two-factor structure that captures higher-order patterns in students' sustainability competencies. In this section, we discuss

(1) the meaning of the seven dimensions in light of existing literature;

(2) the two-factor model that underlies these dimensions;

(3) how the seven dimensions and the two factors can be synthesized into a coherent interpretive framework; and

(4) the implications of the reliability and CFA results for ESD.

Discussion of the Dimensions of Sustainability Competencies Instrument

The findings confirm that sustainable competence is a multidimensional construct encompassing seven interrelated dimensions. The outcomes of the EFA using PCA indicate satisfactory sample adequacy and strong correlations among variables, allowing the establishment of a stable factor structure. The item validity and factor-analytic evidence together support the conclusion that the instrument is of high quality and suitable for assessing the targeted competency construct.

STC

STC is a foundational dimension that enables students to understand complex interconnections within and across social, environmental, and economic systems. In the context of ESD, this competence is essential for helping students grasp the dynamic interactions in natural, social, and economic systems (Schuler et al., 2018). STC involves recognizing how system components interact to shape overall behavior and outcomes (Palmberg et al., 2017; Sengupta & El-Halwagi, 2024). In sustainability contexts, systems thinking helps individuals comprehend the intricate relationships among ecological, economic, and social dimensions; which are further intertwined with cultural, health, and political aspects (Palmberg et al., 2017). This holistic perspective is crucial for tackling complex environmental challenges and promoting sustainable development (Hu & Shealy, 2018; Sengupta & El-Halwagi, 2024). Empirical studies show that educational designs combining field trips, collaborative learning, and mobile learning in real-world environments can foster systems thinking by exposing students to complex systems and diverse perspectives (Demssie et al., 2023). Moreover, systems thinking has been conceptualized as a meta-competence that supports the development of other sustainability competencies by illuminating inter-dependencies among them (Rutherford, 2025). Within our model, STC contributes primarily to the factor associated with critical thinking and sustainable action while also supporting the integrative role of systems understanding across all dimensions.

AC

AC represents a proactive capacity to engage with multiple futures, predict long-term consequences of actions, and navigate uncertainty in sustainability contexts. It is highly relevant in sustainability education because it equips individuals to envision alternative future scenarios and to steer development towards more just and sustainable pathways (Gardiner & Rieckmann, 2015; Ratinen & Linnanen, 2022; Thayer, 2023). AC encompasses skills such as critical reflection on future scenarios, emotional engagement with potential outcomes, and strategic planning (Gardiner & Rieckmann, 2015; Thayer, 2023). Educational interventions designed to strengthen AC typically employ reflective journaling and focus groups to help students evaluate future implications of present actions (Gardiner & Rieckmann, 2015). AC is closely linked to systems thinking and SC, forming a core set of abilities required for addressing complex sustainability challenges (Remington-Doucette & Musgrove, 2015; Sá et al., 2022). It is also central to fostering a culture of sustainability that acknowledges the complexity and unpredictability of living systems (Dominici, 2023). By integrating foresight and long-term decision-making, AC prepares individuals to navigate and influence sustainable futures effectively (Dominici, 2023; Qablan et al., 2025). In the two-factor model, AC aligns strongly with the factor reflecting critical thinking and sustainable action, reinforcing the cognitive-analytical core of sustainability competence.

NC

NC refers to the ability to understand, reflect upon, and formulate values, principles, and goals relevant to sustainability. It provides the ethical foundation that enables individuals to move beyond technical knowledge towards a deeper understanding of "what should be" in sustainability contexts (Bamwell & Hess, 2025; Rousseau, 2017; Schmieg et al., 2018). NC can be understood through three sub-competencies. First, the ability to identify sustainability values and principles, such as intergenerational and environmental justice, which are fundamental to guiding sustainable action (Cano Garcia & Lluch Molins, 2022; Lambrechts et al., 2019; Schmieg et al., 2018; Zapico, 2014). Second, the capacity to evaluate actions and policies against these values by assessing their impact on economic, social, and environmental dimensions as illustrated in sustainable procurement practices (Kinane et al., 2023; Siddhardha et al., 2024). Third, the ability to think critically about prevailing norms, questioning whether existing standards, behaviors, and institutional arrangements adequately promote sustainability (Asrifan et al., 2025; Deer & Zarestky, 2017; Mesa et al., 2022). The development of NC is critical not only in sustainability-focused curricula but also in broader domains such as engineering education, innovation, and entrepreneurship where project-based courses foster innovation competences and help bridge gaps between industry needs and graduate skills (Charosky, 2022). Integrating entrepreneurial education in engineering programs further supports creativity, initiative, and risk-taking—competences that are essential for employability and navigating dynamic labor markets (Bortkevičienė & Vaitkevičius, 2016; Perić et al., 2020). Within our model, NC plays a bridging role, connecting ethical reflection to both the analytical (ML2) and social-collaborative (ML1) factors.

SC

SC is the capability to design and implement effective actions aimed at achieving sustainability goals. It is central in both higher education and organizational contexts, enabling individuals and institutions to respond to complex sustainability challenges through informed decision-making and strategic planning (Cano García & Lluch Molins, 2022; Mach & Ebersberger, 2024; Ruwanika & Massyn, 2024). In higher education, fostering SC involves embedding sustainability into curricula and assessment tasks; thereby, encouraging students to apply theoretical understanding to real-world environmental, social, and economic issues (Cano García & Lluch Molins, 2022). This competence is also increasingly important in innovation management, where it supports the alignment of educational programs with sustainability goals and promotes responsible management practices (Mach & Ebersberger, 2024). In corporate settings,

SC contributes to sustainable competitive advantage through systematic competence management that helps firms adapt to dynamic markets by leveraging their unique capabilities (Ruwanika & Massyn, 2024). Skills such as presencing, intergenerational systemic behavior, and stakeholder engagement form an integral part of SC and are crucial for driving sustainability initiatives and long-term objectives (Ruwanika & Massyn, 2024). Consistent with these perspectives, in our instrument, SC is primarily represented within the factor associated with critical thinking and sustainable action.

CC

CC is essential for working effectively in teams and building partnerships across sectors, cultures, and disciplines in pursuit of sustainability goals. Given the complexity of sustainability problems, solutions necessarily involve multiple stakeholders (Konrad et al., 2020; Krane et al., 2025; Vesterinen & Ratinen, 2024). CC includes the ability to interact productively across different perspectives—whether between scientific disciplines or between scientific and experiential knowledge—which is vital for addressing the multifaceted nature of sustainability challenges (De Kraker et al., 2014). Effective collaboration requires engaging educators, students, professionals, and community members in co-creating solutions to shared problems (Konrad et al., 2020; Krane et al., 2025). Higher education institutions thus have a major role in promoting CC through curricular and assessment innovations that help graduates address real-world sustainability problems (Albareda Tiana & Alférez Villarreal, 2016; Cano García & Lluch Molins, 2022). Collaborative learning approaches, including project-based learning and virtual mobility, have been shown to enhance students' ability to work in diverse teams and engage in meaningful sustainability practices (De Kraker et al., 2014; Demssie et al., 2023; Konrad et al., 2020). These approaches also foster systems thinking by facilitating the exchange of diverse ideas. In the two-factor model, CC is a key contributor to the factor representing social competence and collaboration (ML1).

SAC

SAC is a foundational capacity for recognizing and understanding one's own role, value, and personal impact in supporting sustainability. It is central to sustainability leadership because it promotes reflection on actions and beliefs and supports transformative learning and personal growth (Hunt et al., 2023; Jaakkola et al., 2022). Recent higher education initiatives emphasize self-awareness through experiential pedagogies, where students and faculty jointly develop this competency to prepare students for leading sustainability initiatives. UNESCO has identified self-awareness as a core sustainability competency, and programs designed to develop sustainability competencies often report improvements in self-awareness, highlighting its role in enabling strategic and NCs for sustainable development (van Stigt & Rietbergen, 2022). SAC serves as an internal driver of change, underscoring that sustainability depends not only on macro-level solutions but also on personal actions and reflection. Reflection helps individuals align actions with values and question underlying assumptions, leading to behavioral change (Gouwy, 2014; Shuttleworth et al., 2008).

Personal evolution and self-awareness are thus central to creating a sustainable atmosphere by integrating sustainability into everyday life and work (Gouwy, 2014; Jaakkola et al., 2022). Individual actions and personal competencies, such as self-awareness and emotional resilience, are also essential for engaging with sustainability challenges and promoting sustainable consumption (Frank, 2021; Guerra et al., 2022). Sustainability is therefore deeply rooted in personal reflection and action, complementing broader structural solutions (Quesada-Embid, 2016; Starik et al., 2021). Empirically, SAC contributes meaningfully to the social-collaborative factor (ML1), indicating that self-awareness is tightly linked with relational and socio-emotional dimensions of sustainability competence.

PSC

PSC is the ability to identify, formulate, and resolve complex sustainability-related problems through innovative approaches. It serves as a bridge between theoretical understanding and effective practice. PSC entails systems thinking, interdisciplinary collaboration, and the application of scientific and technical knowledge to real-world challenges (Brundiers et al., 2010; Nasr-Azadani et al., 2023; Vanoye-Garcia & Menchaca-Torre, 2024). Educational approaches such as problem-based learning (PBL) and challenge-based learning (CBL) effectively cultivate PSC by engaging students in authentic problems requiring critical thinking, collaboration, and application of theory (Albareda-Tiana et al., 2024; de Mattos Nascimento et al., 2025; Vanoye-Garcia & Menchaca-Torre, 2024). These methods reinforce critical thinking, collaboration, and technical proficiency. Interactive teaching strategies, including student-led discussions and self-reflection, further enhance key sustainability competencies by inspiring collaborative and participatory learning and problem-solving (Hensley, 2025). These approaches allow students to reconcile differing viewpoints and strengthen their collaborative and communicative capacities. Consequently, PSC is crucial for addressing sustainability challenges by integrating theoretical knowledge with practical application and fostering innovative and workable solutions (de Mattos Nascimento et al., 2025; Nasr-Azadani et al., 2023; Vanoye-Garcia & Menchaca-Torre, 2024). In our factor structure, PSC contributes to both factors, reflecting its dual role in analytical reasoning and social engagement.

Two Factors Underlying the Sustainability Competency Instrument

The EFA, conducted using R Studio with maximum likelihood and parallel analysis, identified two significant main factors (ML1 and ML2), as indicated by eigenvalues above the simulation line, while the eigenvalues of the third and subsequent factors fell below the baseline (Garson, 2022; Li et al., 2020). This justified the selection of a two-factor structure as the most parsimonious representation of the data. The first factor (ML1) primarily explains social competence and collaboration, which strongly supports ESD goals emphasizing the ability to work with others to address sustainability issues. Collaboration is central to achieving the SDGs, where progress depends on collective action at individual, organizational, and national levels. ML1 explains 19% of the variance and includes

items with high loadings such as SAC1 (0.57) and PSC1 (0.65), which reflect collaboration skills and social engagement. These findings align with Eberz et al. (2023), who argue that sustainability competencies encompass the ability to work in teams and build networks for collective action. Conceptually, ML1 is consistent with literature on CC, SAC, and socially oriented aspects of PSC which stress interdependence, shared responsibility, and dialogic problem-solving.

The second factor (ML2) represents critical thinking and sustainable action, contributing 16% of the variance. This factor underscores the importance of analytical capabilities and action-oriented decision-making in ESD, whereby students are expected not only to understand sustainability issues but also to act on them through evidence-based solutions. ML2 reflects students' analytical abilities, as seen in items STC2 (0.60) and AC2 (0.55), consistent with competency frameworks that highlight evidence-based decision-making (Jamil et al., 2024).

Here, systems thinking and ACs play a central role in interpreting complex information and envisioning long-term impacts. The global fit indices further support the adequacy of the two-factor structure. The RMSR index (0.06) and RMSEA (0.075) indicate an acceptable fit, while the TLI (0.809) suggests good—though improvable—model performance (Netson et al., 2024; Xu et al., 2024). The KMO = 0.89 value indicates very good overall sampling adequacy (Nasiru & Dahlan, 2020), as values greater than 0.80 are typically considered adequate for factor analysis (Shrestha, 2021). The MSA for each item exceeds 0.80, with the highest value reaching 0.93 (CC2 and CC3), indicating strong relationships between these items and other variables (Lee et al., 2024; Lorenzo & Ferrando, 2021). The lowest MSA value, 0.81 (AC2), still exceeds the minimum threshold.

The significant Bartlett's test of sphericity ($p < 0.05$) confirms that the correlation matrix is suitable for factor analysis (Eze et al., 2021), satisfying the requirement of sufficiently strong inter-item relationships (Goretzko et al., 2021). The TLI value of 0.809, although below the ideal > 0.90, indicates acceptable reliability (Song et al., 2024). High correlations between the factors and regression scores (ML1 = 0.91; ML2 = 0.88) suggest that both factors effectively capture the underlying construct of sustainability competence. Most items have factor loadings above 0.40, demonstrating strong representation of the two main factors (Hreinsson et al., 2023).

At the same time, the analysis highlights several weaknesses in specific indicators. Item NC1 exhibits a low factor loading, indicating weak measurement of collaboration-related aspects, possibly due to unclear wording or the conceptual complexity of social networks (Fobbe, 2020). Items SAC1-SAC3 show relatively low loadings on ML2, which may reflect the underdevelopment of self-reflection components in current sustainability education (Jaakkola, 2022). Additionally, PSC1-PSC3 indicators are weaker than expected, particularly in problem identification and solution implementation (Mian et al., 2020). These findings emphasize the need to refine particular items to capture critical dimensions of sustainability competence more precisely.

Synthesizing the Seven Dimensions and the Two-Factor Model

A key contribution of this study is the integration of the seven theoretically grounded dimensions with the empirically derived two-factor structure. Rather than viewing the two models as competing, our findings suggest that they are complementary layers of the same construct.

Conceptually, ML1 (social competence and collaboration) integrates the relational and socio-emotional dimensions of sustainability competence. This factor draws heavily on CC, SAC, and the socially embedded aspects of PSC, as shown by the higher loadings of items such as SAC1 and PSC1. Theoretically, this aligns with research emphasizing that sustainability requires teamwork, network-building, and collaborative engagement across disciplinary and sectoral boundaries (De Kraker et al., 2014; Frank, 2021; Guerra et al., 2022; Jaakkola et al., 2022; Konrad et al., 2020; Krane et al., 2025). SAC reinforces the socio-emotional basis of ML1 by anchoring collaborative behavior in personal reflection and values (Gouwy, 2014; Shuttleworth et al., 2008; Starik et al., 2021; van Stigt & Rietbergen, 2022), while PSC contributes through its emphasis on participatory and communicative problem-solving (Albareda-Tiana et al., 2024; Brundiers et al., 2010; de Mattos Nascimento et al., 2025; Hensley, 2025).

By contrast, ML2 (critical thinking and sustainable action) integrates the cognitive analytical and action-oriented dimensions of the framework. This factor is strongly informed by STC, AC, and SC, with NC playing a bridging role. The high loadings of items such as STC2 and AC2 reflect the importance of analytical reasoning, systemic understanding, and future-oriented thinking in sustainability (Gardiner & Rieckmann, 2015; Hu & Shealy, 2018; Jamil et al., 2024; Palmberg et al., 2017; Ratinen & Linnanen, 2022). SC further operationalizes ML2 by translating analytical insights and normative considerations into concrete strategies and actions (Cano García & Lluch Molins, 2022; Mach & Ebersberger, 2024; Ruwanika & Massyn, 2024).

NC links these cognitive-strategic elements to ethical principles and value-based judgments, ensuring that sustainability decisions are not only effective but also just (Kinane et al., 2023; Rousseau, 2017; Schmieg et al., 2018; Siddhardha et al., 2024; Zapico, 2014). In this way, the seven dimensions can be interpreted as first-order specific competences, while ML1 and ML2 function as second order factors that organize these competences into two broader domains:

(1) social-relational engagement, and

(2) critical-strategic action.

This synthesis provides a more compelling and coherent narrative of how sustainability competence is structured: students require both the ability to think systemically and strategically about sustainability problems (ML2) and the relational, reflective, and collaborative capacities to act upon these insights with others (ML1). The integrated model thus captures the dual nature of ESD: it is simultaneously cognitive analytical and relational transformative.

Reliability Analysis

The reliability analysis indicates that the sustainability competencies instrument exhibits excellent internal consistency, with a Cronbach's alpha of 0.88, which falls within the good-to-excellent range ($\alpha > 0.80$) (Kennedy, 2022). The narrow 95% confidence interval (0.87-0.90) further supports the stability of this estimate (Yang et al., 2024). The average inter-item correlation of 0.27 is acceptable but indicates potential for enhancing the coherence of certain item clusters. Most items show item-total correlations (r.drop) above 0.40, satisfying minimum criteria for retention (Nizzolino et al., 2023). Items such as NC2 (0.57) and SAC1 (0.55) contribute strongly to the total score, whereas AC2 (0.36) may warrant revision due to its relatively lower correlation.

An important observation is the stability of the alpha coefficient when items are removed. The alpha remains high across item-deletion scenarios, indicating that the instrument is not dependent on any single item and has achieved an optimal balance in representing the construct of sustainability competence (Maggino, 2023). These results support the use of the scale in diverse educational and research settings and provide a strong basis for more advanced structural analyses, including CFA.

CFA and Implications for ESD

The CFA conducted on a sample of 644 students confirms the validity of the seven dimensions of sustainability competence, with satisfactory model fit indices: CFI = 0.959 (excellent), RMSEA = 0.031 and SRMR = 0.034 (close fit), and TLI = 0.848 (acceptable). These results support a multidimensional approach to measuring sustainability competencies (Bhati, 2020; Ramanan & Mohamad, 2021; Shah, 2019) and indicate that the instrument is valid for capturing complex constructs (Sathyanarayana & Mohanasundaram, 2024). Factor loadings across all dimensions range from 0.47 to 0.67, surpassing the commonly accepted minimum threshold of 0.40 (Hair et al., 2019). PSC and NC show the highest contributions, reaffirming the central role of problem-solving and value-based reasoning in sustainability (Bögeholz et al., 2017; Van Der Hel, 2018). Strategic and CCs exhibit comparatively lower, though still acceptable, loadings; suggesting that these dimensions may benefit from refinement to increase measurement precision (Cui et al., 2022; Ispiryan et al., 2024; Yogindra & Vijaya, 2022). The predominance of loadings above 0.50 across items also underscores the overall reliability of the instrument.

The correlation pattern among factors indicates a complementary and integrative relationship between dimensions of sustainability competence. AC shows very large effects for indicators AC1 (0.988) and AC3 (0.946), with AC2 (0.724) still within a strong range. CC similarly displays large to very large effects (0.994, 0.977), with CC1 (0.527) meeting the threshold for retention. NC indicators (0.751, 0.614, 0.606) fall within the medium-to-large range, indicating adequate convergent validity. PSC exhibits consistent medium-to-large effects (0.642, 0.755, 0.614), while SAC shows very large effects (0.851, 0.982, 0.821). SC presents exceptionally strong measurement accuracy, with loadings of 0.972, 0.931, and 1.002; all within the very large effect category. STC indicators (0.956, 0.916, 0.653) likewise reflect large to very large effects. These findings support the notion that sustainability competencies are interconnected and form an integrative whole in sustainability education (Chaisri, 2024; Costa & Cipolla, 2025; Guerra et al., 2022; Hunt et al., 2023; van Stigt & Rietbergen, 2022).

The use of CFA deepens the understanding of the instrument's structure and reinforces the need for ongoing evaluation and revision to enhance consistency, validity, and reliability in measuring sustainability competencies. CFA is a robust technique for ensuring methodological rigor in competency assessment and for aligning theoretical models with empirical data (Andino-González et al., 2025). It is critical for evaluating internal structural validity and for refining and validating the constructs under study (Rogers, 2024). Furthermore, CFA helps identify gaps in current measurement frameworks and supports the expansion of models to incorporate emerging competencies and context-specific instruments. This iterative process of evaluation and refinement ensures that instruments remain reliable and valid over time (Pacewicz et al., 2024). Overall, the sustainability competency instrument developed in this study provides a valuable tool for supporting ESD. By systematically measuring sustainability competencies, the instrument offers educators actionable data to design and adapt more effective teaching strategies and curricular interventions aimed at preparing students to face sustainability challenges. This aligns with calls for validated assessment tools to measure sustainability competencies as a basis for planning and implementing effective ESD programs (Annelin & Bostrom, 2023; Baena-Morales et al., 2023; Valderrama-Hernández et al., 2025). The combined evidence from the seven dimensions, the two-factor structure, and the reliability and CFA analyses suggests that the instrument not only captures the complexity of sustainability competence but also provides a coherent and empirically grounded framework for its assessment in higher education.

Practical implications

The sustainability competencies instrument created in this study significantly contributes as a framework for evaluating and enhancing human and institutional capacity to tackle sustainability concerns. The specified measuring criteria enhance the conceptual comprehension of sustainability competency and provide actionable direction for educational policy, professional training, and organizational development initiatives. This discovery enables stakeholders — including educational institutions, the industrial sector, and policymakers — to develop curriculum, training programs, and management methods that are more attuned to global sustainability requirements. This instrument has the capacity to facilitate the revision or reconstruction of current sustainability competency theories and offer an empirical foundation for creating more flexible, quantifiable, and long-term impact-focused learning models.

Research Limitations

This study has several shortcomings that warrant consideration. The creation and testing of the sustainability competence instrument were confined to a specific study

program and a restricted number of courses, necessitating further evaluation of the generalizability of the results. To enhance external validity, more research is advised to duplicate the evaluation of this instrument over a broader spectrum of study programs, disciplines, and educational levels. The sample size is relatively small, therefore failing to adequately represent the many features of the students or professionals intended for ongoing competency development.

Recommendations

The sustainability competence measure created in this study should be used into diverse professional education and training programs to evaluate and enhance sustainability capabilities. Educators and program administrators may employ this instrument to develop curriculum, establish learning outcomes, and assess competency attainment in a more quantifiable and thorough manner.

CONCLUSIONS

This study makes a significant contribution to the international literature by developing one of the few empirically validated and theoretically grounded instruments for assessing sustainability competencies in higher education. Through a rigorous four-phase process, the study establishes a reliable and valid measurement instrument encompassing seven core dimensions—STC, AC, NC, SC, CC, SAC, and PSC. The integration of EFA and CFA provides strong empirical confirmation of the instrument's construct validity, revealing a higher-order two-factor structure that captures the dual nature of sustainability competence: social-collaborative competencies and critical thinking-action-oriented competencies. This structural insight advances theoretical understanding by demonstrating how multidimensional sustainability constructs can be synthesized into broader, actionable domains.

The validated instrument offers a robust methodological foundation for strengthening ESD in higher education globally. It enables educators and institutions to systematically diagnose students' sustainability capabilities, align curriculum design with measurable competency outcomes, and evaluate the effectiveness of pedagogical interventions aimed at preparing graduates to address increasingly complex socio-environmental challenges. By providing a psychometrically sound instrument applicable across disciplinary contexts, this study addresses a long-standing gap in sustainability assessment research, where inconsistencies in scale development and limited cross-disciplinary validation have been widely noted.

Future research should extend the applicability of this instrument by testing it across diverse cultural and institutional settings, enabling cross-national benchmarking of sustainability competencies. Complementary qualitative approaches may also deepen understanding of how these competencies develop and manifest in authentic learning environments. Furthermore, the creation of targeted training modules based on the instrument's dimensions holds promise for advancing structured, evidence-based strategies to enhance sustainability competencies at scale. Collectively, the

contributions of this study lay a critical foundation for elevating the global practice of ESD through rigorous assessment, curricular innovation, and competency-driven educational transformation.

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