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Development of a biotechnology literacy instrument for undergraduate science students: Validity and reliability analysis using structural equation modeling

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ABSTRACT

Biotechnology literacy is essential for enhancing students' ability to comprehend and critically assess biotechnological applications. However, standardized biotechnology literacy instruments tailored to the context of science students in Indonesia remain limited. This study aims to test the validity and reliability of a biotechnology literacy instrument using a SEM approach with CFA. A total of 340 science students participated in this study. The instrument tested consisted of 59 items based on the constructs of knowledge, perception, and attitude. The analysis results indicated a reasonably good model fit (RMSEA = 0.071; RMR = 0.028; CFI = 0.903; GFI = 0.909), adequate construct validity (factor loadings = 0.163-0.837), and acceptable internal reliability (CR = 0.62-0.68). Furthermore, the three constructs were significantly correlated, although the correlation coefficients did not all exceed the threshold. These findings confirm that the tested instrument is sufficiently valid and reliable for measuring biotechnology literacy among science students in Indonesia; however, further refinement is needed to improve the quality of measurement.

Keywords: biotechnology literacy, instrument development, construct validity, reliability, structural equation modeling

INTRODUCTION

21st century developments in science and technology have positioned biotechnology as one of the strategic fields that contributes significantly to the health, agriculture, food, and environment sectors (Fırat & Köksal, 2019a; Martin et al., 2021; Unoma & Menkiti, 2017). Modern biotechnology applications, such as genetic engineering, molecular biotechnology, and medical biotechnology, require both mastery of scientific concepts and the ability to understand the social, ethical, and risk implications of their application in everyday life (Henneman et al., 2012; Volet & Vauras, 2013). From a science education perspective, this ability is formulated as biotechnology literacy, which is the competence to understand, evaluate, and make decisions based on biotechnology information rationally and responsibly (Bahri et al., 2014; Carver et al., 2017).

Conceptually, biotechnology literacy is a specific and applied part of science literacy (Bahri et al., 2014; Fırat & Köksal, 2019a). Science literacy includes the ability to understand scientific concepts, use evidence-based reasoning, and apply scientific knowledge in personal and social contexts (Bybee & McCrae, 2011). As a derivative of science literacy, biotechnology literacy not only emphasizes cognitive aspects such as knowledge of biology and biotechnology concepts, but also includes affective dimensions such as perceptions of the benefits and risks of biotechnology and attitudes towards its application as a socio-scientific issue (Lederman et al., 2014; Sutrisna & Anhar, 2020). In line with this, bibliometric studies indicate that research on socio-scientific issues has seen a significant increase over the past two decades, with science literacy emerging as a key focus area encompassing decision-making, scientific argumentation, and an understanding of the nature of science (Özel, 2024). These findings underscore that science literacy is no longer viewed as a single skill but rather as a multidimensional construct.

In the Indonesian context, science literacy remains an educational challenge, as demonstrated by various empirical studies (Afandi et al., 2019; Hartono et al., 2023; Mujakir et al., 2024; Murti et al., 2024; Setiaji et al., 2023). The PISA international assessment results reveal that the science literacy performance of Indonesian students continues to fall below the OECD average, especially in terms of conceptual understanding, scientific reasoning, and the capability to evaluate science-based information (OECD, 2023). This low level of science literacy not only affects primary and secondary education but also has implications for higher education, including the readiness of science students to understand complex and multidimensional scientific issues (Bybee & McCrae, 2011; Lederman et al., 2014). In this context, science students—as future educators, researchers, and professionals in the field of biotechnology—need to possess the ability to analyze various issues related to the application of biotechnology, not limited to global environmental issues (Çelikler & Aksan, 2025), but also encompassing the fields of health, food, and industry (Autade et al., 2015; Castro et al., 2017; Leiva et al., 2025; Ranjha et al., 2022; Toman, 2019). In addition, they also have the capability to assess scientific evidence, understand the benefits and risks, and be able to argue based on science (Alanazi, 2023; de la Hoz et al., 2022; Hafte & Jemal, 2023; Jiménez-Salas et al., 2017; Paš et al., 2019). This is further reinforced by Indonesia's position as a mega-biodiversity country, which is a source of biotechnology potential and has a high need for innovation based on local resources (Hunaefi et al., 2023; Maat, 2014).

Nevertheless, the measurement of biotechnology literacy in Indonesia is still very limited, both in terms of the availability of instruments and the quality of their validity and reliability. The majority of instruments employed in Indonesia are still adaptations of general science literacy and have not been specifically developed for the context of biotechnology (Ntelok et al., 2022; Purbosari & Ma'rifah, 2021; Sofia et al., 2020). At the international level, more comprehensive biotechnology literacy instruments have been developed by previous researchers. Some of these measure the dimensions of knowledge, perception, and attitude but do not provide detailed information regarding validity and reliability testing (Bahri et al., 2014; Prokop et al., 2007), while others focus solely on measuring the attitude dimension (Erdogan et al., 2009; Klop & Severiens, 2007), conceptual understanding and application (Fırat & Köksal, 2019a); knowledge, attitudes, awareness, and interest (Firat et al., 2021). However, these instruments generally focus on modern biotechnology. In the Indonesian context, aspects of conventional biotechnology are also highly relevant, so conventional biotechnology needs to be an integral part of literacy assessments. Furthermore, the literature also notes that conventional biotechnology serves as the cornerstone of global biotechnology (Nascimento & Barros, 2025) and biotechnology literacy must encompass both (Yee et al., 2025).

The development of biotechnology literacy instruments must be based on a clear theoretical framework, validated through rigorous psychometric procedures, and integrate authentic socio-scientific contexts to reflect real-world biotechnology issues (Özel, 2024). The findings of Erdogan et al. (2009) indicate that measurements in the field of biotechnology require valid and reliable instruments. Furthermore, a good instrument must be able to capture a multidimensional construct structure (Erdogan et al., 2009; Fırat & Köksal, 2019a), and be tested using robust statistical methods like Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM) (Hair & Alamer, 2022; Taber, 2018). CFA allows researchers to test construct validity by assessing the suitability of indicators to latent constructs, while SEM provides a comprehensive framework for evaluating the reliability and suitability of measurement models simultaneously (Hair & Alamer, 2022). Thus, these conditions highlight the urgency of developing specific, valid, and reliable instruments for measuring the biotechnology literacy of science students in Indonesia.

MATERIALS AND METHODS

Research Design

A quantitative research approach was utilized in this study using an instrument development and validation design conducted from January to June 2024. This study primarily aimed to evaluate the factor structure, construct validity, and reliability of the biotechnology literacy instrument using a covariance-based SEM approach. This approach was applied because it is capable of comprehensively evaluating measurement models and assessing the suitability between theoretical constructs and empirical data.

Participants

The study participants consisted of 340 science students who had completed courses in basic biology and biotechnology. This sample size was considered sufficient to meet the minimum recommended requirements for SEM analysis, thereby allowing for stable and accurate estimation of model parameters.

Instrument Development

The biotechnology literacy instrument was constructed with reference to a thorough review of the scientific literacy literature, biotechnology literacy, and biotechnology-related socio-scientific issues. The instrument was designed to measure three main constructs based on previous theoretical and empirical studies (Bahri et al., 2014; Fırat & Köksal, 2019a; Klop & Severiens, 2007; Prokop et al., 2007), namely:

(1) Knowledge, representing an understanding of fundamental biological and biotechnological concepts;

(2) Perception, describing individuals' perceptions of the benefits, risks, and ethical and moral aspects of biotechnology; and

(3) Attitude, reflecting individuals' attitudes toward the acceptance, use, and implications of biotechnological applications.

Although some general literacy or educational evaluation frameworks include a behavioral dimension, this dimension is often not directly measured in the context of biotechnology literacy. The affective and behavioral dimensions are strongly correlated and help explain individuals' tendencies to act on biotechnology-related issues (Nordqvist & Johansson, 2020). Furthermore, actual behavior is influenced by various external factors, such as social and cultural contexts as well as access to technology, and therefore does not necessarily directly reflect an individual's level of literacy (Schrader et al., 2007). Therefore, this study focuses its measurements on the dimensions of knowledge, perception, and attitude as the primary representations of biotechnology literacy that are more relevant in an educational context.

Table 1. Description of the biotechnology literacy instrument indicators

Constructs	Code	Description of indicators	Number of statements	Sample statements
Knowledge	K1	Biology & genetic	14	Genetic manipulation of DNA can produce new beneficial traits.
	K2	Microbiology	6	Microbes aid in the fermentation of food.
	K3	Basics of biotechnology	5	Conventional biotechnology utilizes fermentation techniques.
Perception	P1	Ethics-related perceptions	3	All animals can be used directly in biotechnology.
	P2	Perceptions of the benefits of biotechnology	3	Biotechnology helps improve food quality.
	P3	Perceptions of biotechnology risks	4	Genetic modification can lead to the loss of native species.
	P4	Perceptions related to religion and morality	4	Modern biotechnology is perceived as a form of blasphemy against religion.
Attitude	A1	Acceptance of the use of biotechnology products	4	I'm hesitant to consume fermented food and beverage products because they contain alcohol.
	A2	Acceptance of biotechnology applications in agriculture	4	I support genetically modifying plants so they can grow better in salty soil.
	A3	Awareness of biotechnology applications	3	I support the current government regulations because they adequately protect the public from the risks posed by genetically modified foods.
	A5	Ethical acceptance of biotechnology	3	I agree that DNA manipulation is unethical.
	A6	Environmental impact–based acceptance and rejection of biotechnology	2	I agree that genetic modification can disrupt the balance of an ecosystem.
	A7	Acceptance of biotechnology in healthcare	4	I support the use of genetic engineering in the production of human medicines.

In the initial stage of development, the instrument consisted of 14 indicators comprising 63 items. The knowledge (K) construct was measured using three indicators (K1-K3), perception (P) using four indicators (P1-P4), and attitude (A) using seven indicators (A1-A7). Based on the results of the measurement model evaluation, one indicator within the attitude construct was eliminated because it did not meet the criteria for construct validity. That indicator is A4 (purchase of biotechnology products), which consists of 4 items. Consequently, the final measurement model of the biotechnology literacy instrument consisted of 13 indicators (59 items) that satisfied both statistical and theoretical criteria. This instrument has also been evaluated by three experts—a science literacy expert, a biotechnology learning assessment expert, and a general biotechnology expert—and has been found to have good content validity with minor revisions.

All indicators were presented as closed-ended statements measured on a Likert scale from 'strongly disagree' (score = 1) to 'strongly agree' (score = 5). The measurement scale used in this instrument is based on the results of previous studies (Bahri et al., 2014; Klop & Severiens, 2007; Prokop et al., 2007). This Likert scale with an odd number of response options is capable of reducing measurement error compared to the use of a Likert scale with an even number of response options (Bahri et al., 2014). **Table 1** presents a description of the indicators for each construct. A more detailed description of the indicators and their corresponding statements is presented in **Table A1** in **Appendix**.

Data Collection

Online questionnaires were used to collect data from respondents. Prior to analysis, data was selected to ensure the completeness and validity of responses. Only complete datasets that satisfied the SEM analysis criteria were included in subsequent analyses.

Data Analysis

A covariance-based SEM approach with AMOS software was used to analyze the data. The analysis procedure was carried out in stages as follows.

Model specification

The SEM model analyzed consists of two main components: The measurement model and the structural model. The measurement model is employed to examine the relationship between indicators and latent constructs using Confirmatory Factor Analysis (CFA), while the structural model is used as supporting analysis to evaluate the interrelationships between constructs.

Model fit evaluation

Evaluation of model fit was conducted based on several Goodness of Fit (GoF) indices, including Chi-square, Root Mean Square Error of Approximation (RMSEA), Standardized Root Mean Square Residual (RMSR/RMR), Normed Fit Index (NFI), Comparative Fit Index (CFI), and Goodness of Fit Index (GFI). The model is considered acceptable if the goodness-of-fit index values meet the criteria recommended in the SEM literature. The GoF value criteria are summarized in **Table 2**.

Table 2. GoF value criteria

Criteria	Value
Chi Square (λ^2) or	Chi-square < λ^2 (α;df) = Chi-square table value
Sig. Probability Chi Square	≥ 0.05
RMSEA	≤ 0.08
RMSR	≤ 0.1
NFI	≥ 0.90
CFI	≥ 0.90
GFI	≥ 0.90

Source: Hair & Alamer (2022); Schermelleh-Engel et al. (2003)

Table 3. Respondent characteristics

Variables	Category	Frequency	Percentage (%)
Study programs	Biology	40	11,76
	Biology education	260	76,48
	Science education	40	11,76
Gender	Male	63	18,52
	Female	277	81,48
Semester	5	199	58,53
	7	141	41,47

Note: n = 340

Table 4. Measurement model goodness-of-fit indices

	χ^2	df	p	RMSEA	RMR	NFI	CFI	GFI
GoF Value	267.93	57	0.000	0.071	0.028	0.889	0.903	0.909

Construct validity assessment

Construct validity was evaluated using CFA, taking into account factor loading values, t-statistics values, and p-values for the relationship between indicators and latent constructs. Indicators were deemed valid if they had a significant relationship with the construct (χ^2/df < 3; $p < 0.05$) (Hair & Alamer, 2022). In addition, construct validity was also evaluated based on the suitability of the factor structure with the proposed theoretical model.

Reliability assessment

Construct reliability was determined through Composite Reliability (CR) and Average Variance Extracted (AVE) measures. A CR value ⩾ 0.60 was used as the criterion for acceptable reliability, while the AVE value ⩾ 0,50 was used as an additional indicator to evaluate the construct's internal consistency (Fornell & Larcker, 1981; Hair & Alamer, 2022). The construct was declared reliable if the CR value met the criteria, even if the AVE value was below the ideal limit.

Structural model analysis

As a supporting analysis, a structural equation model was tested to evaluate the relationships among the latent constructs. In addition to assessing the consistency of these relationships with the theoretical framework of biotechnology literacy, this analysis also provides an indication of discriminant validity—that is, the extent to which each construct can be empirically distinguished from the others. Significant but not overly high relationships between constructs indicate that each construct plays a distinct role and does not overlap. The significance of the relationships was tested using t-statistics and p-values at a 5% significance level (Hair & Alamer, 2022).

RESULTS

Respondent Characteristics

The characteristics of the respondents involved in this study are described in **Table 3**. As summarized in **Table 3**, this study involved 340 science students as respondents. Respondents came from various study programs in the science cluster who had taken basic biology and biotechnology courses. Respondent distribution across semesters shows that the majority of respondents were in the middle to final semesters of their studies. The gender composition of respondents indicates a higher proportion of female than male participants. Overall, the research sample had relevant and adequate characteristics to facilitate the evaluation of the developed biotechnology literacy instrument in terms of its validity and reliability.

Evaluation of Measurement Model Suitability (Goodness of Fit)

The analysis of the suitability of the measurement model was conducted using a covariance-based SEM approach through the CFA method. **Table 4** presents the analysis results of model fit. **Table 4** indicates that the measurement model has a fairly good level of fit, as indicated by p-value < 0.05, RMSEA (0.071), and RMR (0.028) values that are within the acceptable range. In addition, other fit indices, namely CFI (0.903) and GFI (0.909), have met the recommended criteria (⩾ 0.90). However, the χ^2/df value does

Table 5. Construct validity results

Factor variables (constructs)	Indicator variables	Standardized (factor loadings)	Weights	p-values
Knowledge	K1	0.481	1	Fix parameter
	K2	0.721	2.056	0.00
	K3	0.61	1.792	0.00
Perception	P1	0.388	1	Fix parameter
	P2	0.47	0.894	0.00
	P3	0.62	1.577	0.00
	P4	0.837	2.556	0.00
Attitude	A1	0.753	1	Fix parameter
	A2	0.344	0.301	0.00
	A3	0.163	0.172	0.006
	A5	0.71	0.833	0.00
	A6	0.521	0.682	0.00
	A7	0.206	0.211	0.00

Table 6. Construct reliability test results

Factor variables (constructs)	CR	AVE
Knowledge	0.64	0.4
Perception	0.68	0.4
Attitude	0.62	0.3

not yet meet the criterion (< 3), and the NFI value (0.889) indicates that there is still a mismatch between the model and the empirical data. These findings indicate that the measurement model of the biotechnology literacy instrument fits the empirical data quite well, making it sufficiently adequate for use in evaluating the construct validity and reliability of the instrument.

Construct Validity Test Results

Construct validity was evaluated using standardized factor loading values, t-statistics, and p-values of indicator–construct associations. **Table 5** shows the results of construct validity testing through CFA. As shown in **Table 5**, the CFA results in the final model show that all indicators are significantly associated with their respective constructs ($p < 0.05$). The factor loading values of the indicators ranged from 0.163 to 0.837. Although some indicators have loading values below 0.50, all indicators were retained because they demonstrate statistically significant relationships and have a sufficiently strong theoretical foundation for representing the construct of biotechnology literacy. Thus, these results provide empirical evidence that the developed indicators are sufficiently valid for assessing the constructs of knowledge, perception, and attitude.

Construct Reliability Test Results

Construct reliability was assessed based on CR and AVE values. Results from the construct reliability test are shown in **Table 6**. Results reported in **Table 6** reveal that the CR values for all constructs are in the range of 0.62-0.68, which meets the minimum reliability criteria (CR $\geqslant$ 0.60). The AVE values fall within the range of 0.30 to 0.40, which is below the ideal limit of 0.50. Based on methodological recommendations, constructs with adequate CR values can still be considered reliable even if the AVE values are relatively low. Therefore, the three constructs in this biotechnology literacy instrument are considered to have acceptable internal reliability, especially for early-stage instrument development research.

Biotechnology Literacy Instrument Model

The biotechnology literacy instrument model adopted in this study is presented in **Figure 1**. **Figure 1** shows the CFA results in the final model, where the biotechnology literacy instrument is confirmed to have three dimensions, namely knowledge, perception, and attitude. This construct structure is consistent with the theoretical framework of biotechnology literacy, which combines cognitive and affective dimensions. The association between the indicators and latent constructs shows a stable and significant pattern, thus providing empirical evidence that the developed instrument has a clear and statistically confirmed construct structure.

Structural Model Analysis

As a supporting analysis, structural model testing was conducted to evaluate the relationship between latent constructs. The results of the structural model analysis examining relationships among constructs are summarized in **Table 7**. Results reported in **Table 7** reveal that knowledge has a statistically significant effect on attitude ($\beta = 0.233$, $p < 0.05$), while perception shows a stronger effect on attitude with a standardized coefficient of 0.870 ($p < 0.05$). In addition, knowledge and perception are significantly correlated, with a correlation coefficient of 0.218 ($p = 0.012$). Empirical evidence from this study indicates that the relationship between constructs in the instrument is consistent with the theory of biotechnology literacy. Evaluation of the coefficient of determination shows an R^2 value of 0.90, suggesting that a substantial proportion of variance in the attitude construct is explained by the knowledge and perception constructs. Overall, the analysis results indicate that the developed biotechnology literacy instrument has a suitable measurement model, adequate construct validity, and acceptable internal reliability.

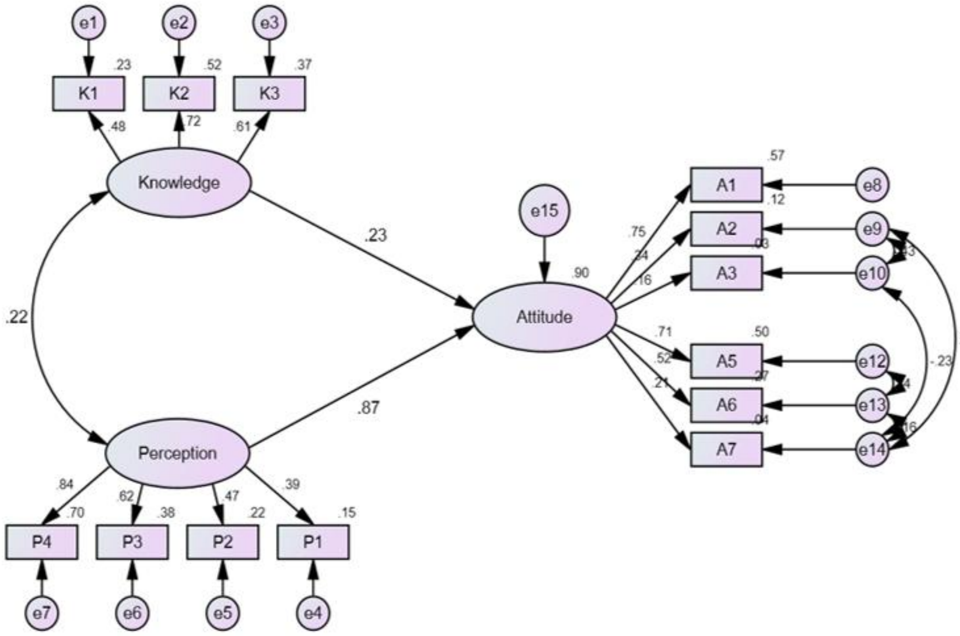

Figure 1. SEM model of biotechnology literacy instruments: standardized estimates

Table 7. Assessment of relationships between latent constructs

Exogenous variable	Endogenous variable	Standardized estimates	Regression estimates	p-value	Conclusion
Knowledge	Attitude	0.233	1.028	0.00	Significant
Perception	Attitude	0.870	1.917	0.00	Significant
Knowledge	Perception	0.218	0.008	0.012	Significant

DISCUSSIONS

This study examines the quality of a biotechnology literacy instrument based on its validity and reliability, covering the dimensions of knowledge, perception, and attitude. The three-dimensional factor structure consisting of knowledge, perception, and attitude confirms that biotechnology literacy is a multidimensional construct (Fırat & Köksal, 2019a). This is consistent with studies on science literacy that emphasize that applied science literacy encompasses both conceptual comprehension and the assessment of social implications, as well as the development of attitudes toward science and technology (Bybee & McCrae, 2011; OECD, 2023). The integration of cognitive and affective dimensions in a single instrument reflects the complex and contextual nature of biotechnology issues (Fırat & Köksal, 2019a; Hodson, 2011; Sadler & Zeidler, 2009).

The instrument proposed in this study is a contextually adapted version of previous studies that generally focused on modern biotechnology (Bahri et al., 2014; Fırat & Köksal, 2019a; Klop & Severiens, 2007; Prokop et al., 2007). Unlike previous studies, the instrument in this study covers not only modern biotechnology but also conventional biotechnology. In the Indonesian context, the focus on biotechnology literacy is not limited to modern biotechnology but also includes conventional biotechnology, particularly fermentation processes based on local microorganisms that have become an integral part of local culture (Setiarto et al., 2024). Furthermore, science literacy—particularly in biotechnology—must be conceptually linked to real-life and cultural contexts (Firat & Köksal, 2019b; OECD, 2018; Özel, 2024). Thus, the instrument is considered more suitable for the needs of the educational context in Indonesia.

The findings indicate that the final measurement model exhibits a reasonably good level of fit overall. Model fit is a key indicator that the proposed construct structure is consistent with the underlying data and theory, particularly in CFA-based instrument development research (Hair & Alamer, 2022; Kline, 2016). However, not all fit indices in this study yielded optimal results. This indicates that the model still has some limitations that need to be addressed. In the context of evaluating measurement models, it is recommended not to rely solely on a single fit index, but rather to consider a combination of several indices simultaneously (Hair & Alamer, 2022). Therefore, considering that most of the primary indices have met the recommended criteria, the measurement model in this study can still be considered valid and adequate for use in subsequent analysis stages.

The instrument's construct validity is supported by the results of CFA (Akcan & Başaran, 2022). The significant relationship between the indicators and the constructs shows that the developed indicators are capable of empirically represent the conceptual domain of biotechnology literacy (Brown, 2015; Hair & Alamer, 2022). Hair and Alamer (2022) recommend factor loadings > 0.50 to meet the criteria for convergent validity, whereas Cheung et al. (2024) states that values > 0.40 are still acceptable. However, the findings indicate that the factor loadings for some indicators do not yet meet the recommended criteria. In this study, relatively low factor loadings indicate that these indicators have a weak contribution in representing the latent construct. According to Hair and Alamer (2022), standardized factor loadings below 0.7 indicate that the factor explains less than

50% of the item variance, so this requires evaluation. Furthermore, the presence of indicators with low loadings is not always viewed as a weakness but rather as part of the empirical evaluation process to identify indicators that need refinement or reconstruction (Hair & Alamer, 2022). The variation in factor loading values observed in this study reflects the complexity of students' responses to biotechnology issues, which is a common characteristic in the measurement of science literacy involving socio-scientific contexts (Sadler et al., 2007; Sadler & Zeidler, 2009).

The reliability analysis indicates that all constructs have CR values that are in the acceptable category. These findings indicate that the instrument has sufficient internal consistency to be used in educational research and learning evaluation (Hair & Alamer, 2022; Mcneish, 2017). However, the AVE values for all constructs have not yet met the recommended criteria, which means that the indicators are not yet strong enough to adequately explain the constructs being measured. Relatively low AVE values are still acceptable in the context of early-stage instrument development research, especially when the CR values meet the minimum criteria and the indicators have a strong theoretical basis (Hair & Alamer, 2022; Malhotra, 2020).

The establishment of a three-dimensional factor structure contributes theoretically to the study of applied science literacy, particularly biotechnology literacy. This structure is consistent with the science literacy approach that emphasizes the relationship between scientific knowledge, risk and benefit assessment, and attitudes toward the application of science and technology (Bybee & McCrae, 2011). Thus, this instrument offers a more comprehensive measurement approach than general science literacy instruments, which tend to focus on cognitive aspects (Fırat & Köksal, 2019a).

The significant relationship between knowledge and perception on attitude supports the appropriateness of the relational structure between constructs and the theoretical framework underlying biotechnology literacy. These findings support the view that attitudes toward biotechnology are shaped by a combination of conceptual understanding and individual perceptions of the social, ethical, and technological implications of this technology (de la Hoz et al., 2022; Firat et al., 2021; Fırat & Köksal, 2019b; Hin et al., 2019; Kamizi & Iksan, 2021; Li & Ma, 2024; Sadler et al., 2007). This is an important component in the validation of SEM-based instruments to ensure that constructs are not only statistically valid but also theoretically meaningful (Hair & Alamer, 2022; Kline, 2016). However, the literature indicates that correlation coefficients between constructs should fall within the range of 0.85-0.90 to ensure adequate discriminant validity (Hanseler et al., 2009). Thus, although the relationships among the constructs in this study are significant and consistent with the theoretical framework, the fact that the correlation coefficients do not all exceed that threshold indicates that each construct retains distinct characteristics and does not overlap conceptually (Cheung et al., 2024). This indicates that the constructs of knowledge, perception, and attitude can be empirically distinguished, thereby supporting the fulfillment of discriminant validity in the developed measurement model.

On the other hand, some studies have not reported a significant relationship among the variables of biotechnology literacy (Casanoves et al., 2015; Erdoğan et al., 2012; Li & Ma, 2024; Öztürk-Akar, 2017; Šorgo, 2012; Usak et al., 2009). A study conducted by Li and Ma (2024) found that the level of knowledge about biotechnology remains low or moderate among students and university students, particularly regarding basic concepts of genetics and technological applications such as GMOs, although general attitudes toward their application range from neutral to positive (Li & Ma, 2024). Furthermore, Prokop et al. (2007) found that individuals with a high level of knowledge do not necessarily exhibit positive attitudes if they have a high perception of the risks associated with biotechnology. Perceptions of risk or perceived lack of benefits of biotechnology products often influence rejection of products such as GMOs more than technical knowledge alone (Jiménez-Salas et al., 2017; Li & Ma, 2024; Medani et al., 2024). These findings are reinforced by Nurlaely et al. (2017), who noted that the influence of knowledge on attitudes becomes significant when mediated by perceptions of the benefits and implications of biotechnology. This relationship indicates that knowledge alone does not automatically lead to a mature understanding of the social and ethical implications of biotechnology (Hin et al., 2019).

Research on public perceptions of biotechnology has shown differences in the assessment of the risks and benefits of the technology between expert and non-expert groups (Savadori et al., 2004). Medani et al. (2024) reinforce that perceptions are based not only on scientific information but also on social experiences and cultural values, and are mediated by exposure to biotechnology issues in the mass media (Jiang & Wang, 2024; Nawaz et al., 2025; Torres et al., 2006; Zhang et al., 2026). Furthermore, sources of information about biotechnology involving mass media and interpersonal interactions tend to influence the public's views on whether biotechnology is beneficial or not (Jiang & Wang, 2024; Nawaz et al., 2025; Torres et al., 2006; Zhang et al., 2026). Bahri et al. (2014) explain that the level of perception regarding biotechnology among students may be attributed to limited access to relevant information needed to address controversial biotechnology issues. Additionally, Firat et al. (2021) also noted that exposure to misinformation about biotechnology through various media and the internet has the potential to lead to the adoption of inaccurate ideas, thereby fostering incorrect perceptions that will influence attitudes.

Other studies indicate that younger students hold more negative attitudes toward biotechnology compared to older students (Chen & Raffan, 1999; Dawson, 2007; Usak et al., 2009). This is likely due to younger students' lower level of knowledge regarding specific topics as well as science in general (Alanazi, 2023). Nevertheless, attitudes are not rigid psychological constructs that are unresponsive to change. Certain interventions, such as educational interventions that engage students in specific tasks, can alter more complex affective constructs in real time (Volet & Vauras, 2013). Some studies have even found that people's attitudes toward biotechnology applications change over time. Research by Henneman et al. (2012) shows that over an 8-year period, the Dutch public's attitudes toward the benefits and potential uses of genetic testing have improved. Medani et al. (2024) also found that appropriate education can enhance understanding of the risks and benefits of biotechnology. This supports the need for improved instructional design that not only enhances factual knowledge but also facilitates a deeper understanding of complex issues.

Within Indonesia's higher education context, the existence of valid and reliable biotechnology literacy instruments is essential in addressing the problem of low science literacy in Indonesia based on the results of international assessments. More specific, contextual, and reliable instruments serve to map students' abilities in understanding biotechnology issues (OECD, 2023); evaluate learning, curriculum development, and evidence-based science education design (Bybee & McCrae, 2011; Hodson, 2011); and supporting improvements in the quality of science education (Fırat & Köksal, 2019a; Hair & Alamer, 2022).

CONCLUSIONS

This study contributes to the development of a multidimensional biotechnology literacy instrument (knowledge, perception, and attitude) grounded in socio-scientific issues relevant to the development of modern and conventional biotechnology, thereby better aligning with the realities of education in Indonesia. Furthermore, the instrument has been tested using an adequate psychometric approach, providing initial empirical evidence regarding construct structure, validity, and reliability-aspects rarely reported comprehensively in similar studies. These findings confirm that the measurement model exhibits sufficient fit, with adequate construct validity and acceptable internal reliability. The indicators developed generally represent the construct of biotechnology literacy, and the relationships among the constructs (knowledge, perception, and attitude) are consistent with the underlying theoretical framework.

Nevertheless, this study has several limitations. First, some indicators do not yet fully meet ideal criteria, such as model fit values, factor loadings, AVE, and inter-construct correlations, indicating the need for further refinement to improve measurement quality. Second, the study sample is limited to science students who have taken biotechnology courses, so the generalizability of the findings still needs to be tested on a broader and more diverse population.

Theoretically, this study reinforces the understanding that biotechnology literacy is a multidimensional construct encompassing cognitive and affective dimensions within the context of socio-scientific issues. Methodologically, this study contributes through the development and evaluation of an SEM-CFA-based instrument that can serve as a reference for future research in the measurement of applied science literacy.

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APPENDIX

Table A1. Description of statements in the biotechnology literacy instrument

No.	Construct	Code	Indicator	Statements
1	Knowledge	K1	Biology & genetic	DNA contains the genetic information for all hereditary traits.
				Genetic modification causes mutations in animal and plant cells.
				Normal tomatoes differ from genetically modified tomatoes, which lack the gene.
				DNA manipulation is performed by altering the genetic makeup of an organism.
				Consuming genetically modified foods can be harmful to human genes.
				Genetic modification in animals can improve their resistance to disease
				Genetic modification of plants can improve the nutritional quality and taste of fruits and slow down spoilage.
				Foods with higher nutritional value and vitamin content can be produced through genetic modification.
				The transfer of genetic material between organisms, including between animals and plants, is possible because DNA has an identical chemical structure.
				Genetically modified organisms are used in medicine (for example, in insulin production).
				Genetically modified organisms are always larger than normal organisms.
				Genetically modified organisms contain hazardous chemicals.
				Genetically modified plants are fertile.
				Genetic manipulation of DNA can produce new beneficial traits.
		K2	Microbiology	Microbes must be genetically engineered to make them more efficient at breaking down waste.
				Microbes aid in the fermentation of food.
				The microorganisms involved in food fermentation are harmless microorganisms.
				Fermented food products can be harmful to health.
				Microbes can help restore environments contaminated with heavy metals.
				Alcoholic beverages are made using microorganisms.
		K3	Basis of biotechnology	Conventional biotechnology utilizes fermentation techniques.
				Genetically modified plants contain harmful genes when consumed.
				Biotechnology products offer benefits in the field of health.
				Conventional biotechnology is widely used to produce nutritious food products.
				Through tissue culture, many new plants identical to the parent plant can be produced.
2	Perception	P1	Ethics-related perceptions	All animals can be used directly in biotechnology.
				Humans can modify the genetic makeup of animals if they do not feel pain.
				Humans have the right to modify living organisms.
		P2	Perceptions of the benefits of biotechnology	Biotechnology produces food and beverage products that help combat hunger.
				Agricultural biotechnology is harmful to farmers' livelihoods.
				Biotechnology helps improve food quality.
		P3	Perceptions of biotechnology risks	Biotechnology products raise concerns among the people who consume them.
				Genetic modification can lead to the loss of native species.
				Biotechnology threatens the natural order.
				Genetic modification can lead to the transmission of diseases from animals to humans.
		P4	Perceptions related to religion and morality	Biotechnology is playing God by creating individuals with new traits.
				Biotechnology reduces living beings to mere machines.
				Modern biotechnology is perceived as a form of blasphemy against religion.
				Conventional biotechnology has produced food and beverage products that are not halal because they contain alcohol.
3	Attitude	A1	Acceptance of the use of biotechnology products	I oppose the genetic modification of fruits and vegetables to make them stay fresh longer.
				I won't give my children genetically modified food.
				I don't eat genetically modified foods because they pose a health risk.
				I'm hesitant to consume fermented food and beverage products because they contain alcohol.
		A2	Acceptance of biotechnology applications in agriculture	I support food biotechnology that modifies plant genes to make them resistant to insect attacks, thereby reducing the use of pesticides.
				I agree with the use of genetically modified plants to improve crop quality and productivity.
				I support genetically modifying plants so they can grow better in salty soil.
				I oppose the production of seedless fruits because it eliminates their ability to reproduce naturally.
		A3	Awareness of biotechnology applications	I believe that the food industry has taken the necessary steps to ensure the safety of genetically modified foods.
				I support the current government regulations because they adequately protect the public from the risks posed by genetically modified foods.
				The public receives sufficient information from producers about the risks associated with genetically modified foods.

Table A1 (Continued). Description of statements in the biotechnology literacy instrument

No. Construct	Code	Indicator	Statements
3 Attitude	A5	Ethical acceptance of biotechnology	I oppose the transfer of genetic material between plants and animals.
			I agree that DNA manipulation is unethical.
			Creating new individuals with new traits through genetic engineering is unethical.
	A6	Environmental impact–based acceptance and rejection of biotechnology	I agree that genetic modification can disrupt the balance of an ecosystem.
			There is a risk of hybridization between genetically modified plants and conventional plants, which could endanger the native genetic resources of plants.
	A7	Acceptance of biotechnology in healthcare	I support the use of genetic engineering because it helps treat genetically determined diseases.
			I support the use of genetic engineering in the production of human medicines.
			I agree with the production of insulin using genetically modified microorganisms.
			I agree with the use of live microorganisms in the production of biotechnology products such as yogurt.