Assessment of scientific competencies in secondary school students: exploring the relationships among inquiry, explanations of the physical world, and the design of technological solutions

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ABSTRACT

Assessing scientific competencies in secondary education requires understanding their structural relationships, yet limited research examines these interrelationships empirically. This study investigated how scientific inquiry, explanation of physical phenomena, and design of technological solutions interact in 165 Peruvian secondary students using partial least squares structural equation modeling (PLS-SEM). Results confirmed that inquiry significantly influences both explanation and design capabilities, while explanation mediates the relationship between inquiry and design. The model demonstrated excellent fit (standardized root mean square residual (SRMR)=0.068, normed fit index (NFI)=0.912)), explaining 67.3% of variance in explanation and 71.8% in design. Findings establish inquiry as the foundational competency for developing explanatory and problem-solving abilities, supporting integrated curriculum design and sequential pedagogical approaches that prioritize inquiry development.

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1. INTRODUCTION

The assessment of scientific competencies in secondary school students is a multidimensional educational challenge documented across multiple international contexts. Programme for International Student Assessment (PISA) assessments reveal consistent deficiencies in students' scientific mastery, particularly in their ability to explain phenomena scientifically, evaluate and design scientific research, and interpret data and evidence [1], [2]. Secondary school students often face difficulties with problem identification, hypothesis formulation, conclusion drawing, and experimental design, with limited progress across educational levels [3].

These limitations are particularly evident when students experience challenges in distinguishing authentic inquiry questions from informational questions, which require structured dialog between teachers and students to develop investigative skills [4]. Current assessment frameworks emphasize core components such as question and hypothesis formulation, experimental design, data analysis, and conclusion drawing, although validated instruments reveal limitations in capturing authentic inquiry skills [5], [6]. Additionally, scientific literacy generally remains low, with significant gaps in thinking, methodology, and application [7], whereas difficulties persist in mastering scientific inquiry skills, especially in experimental design and data recording, which require specific scaffolding [8].

Despite widespread recognition of inquiry-based learning for developing scientific competencies [6], [9], a critical gap persists: the absence of empirical models quantifying causal relationships between different competency domains. Existing research predominantly examines competencies in isolation rather than their structural interdependencies [10], [11]. This limitation prevents understanding how mastery in one domain (e.g., inquiry) influences development in others (e.g., explanation or design).

Current assessment frameworks face several challenges. Many instruments fail to capture multidimensional complexity, necessitating mixed-method approaches for deeper insights [10], [11]. Research shows limited correlations between pedagogical factors and student competence [12], suggesting unexplored mechanisms. Emerging frameworks like model-based reasoning demonstrate potential for improving explanations and confidence [13], [14], yet students often perceive scientific inquiry as irrelevant, affecting engagement [15], [16]. Critically, sub competencies such as hypothesis generation, experimental design, and data analysis remain underutilized in assessments [9]. This study addresses these gaps by employing structural equation modeling (SEM) to establish directional relationships between inquiry, explanation, and design competencies, providing empirical evidence for integrated pedagogical interventions.

This research analyzes three central constructs derived from the scientific competencies curriculum framework: i) scientific inquiry (IN), which encompasses the formulation of researchable questions, the design of experimental strategies, the generation and analysis of data, and the critical evaluation of research processes; ii) explanation of physical phenomena (EX), which involves the understanding and application of knowledge about living beings, matter, energy, biodiversity, Earth, and the universe to interpret natural phenomena and evaluate technological implications; and iii) design of technological solutions (DE), which encompasses the identification of technological alternatives, the detailed design of solutions, the implementation and validation of prototypes, and the critical evaluation of the functioning and impact of technological developments.

These constructs reflect the authentic nature of scientific practice and are essential for fostering scientific literacy and student problem-solving skills, integrating content knowledge with inquiry processes to support a holistic view of scientific competence [17], [18]. In the Peruvian context, the assessment of scientific competencies faces specific challenges documented in the regional literature. PISA tests administered in Peru reveal persistent deficiencies in student scientific competencies, requiring competency-based and contextualized teaching approaches [19]. Formative assessment has been shown to have significant effects on the development of scientific and technological competencies through continuous feedback and adaptive instruction, particularly benefiting lower-performing students [20], [21].

The use of specific rubrics and structured sequences facilitates the assessment of research and data interpretation skills, although limitations persist in competency-based teaching, the lack of appropriate assessment tools, and disparities in digital skills between genders [1], [22]. Traditional pedagogical approaches can limit the development of inquiry skills, whereas student-centered methods demonstrate greater effectiveness [23], [24]. The implementation of design thinking has shown potential for developing design and technological solution-building skills in science and technology courses [25], although best practices require the deliberate inclusion of core scientific and technological skills during educational planning, comprehensive teacher training, and the integration of scientific and technological skills into the curriculum [26]. Curriculum reforms in Peru seek to promote scientific learning and the development of competencies related to the design and construction of technological solutions to solve environmental problems, although the effective implementation of these reforms faces obstacles related to teacher preparation and the availability of appropriate resources.

The overall objective of this study is to determine the structural relationships among scientific inquiry skills, explanations of the physical world, and the design of technological solutions for secondary school students through partial least squares SEM (PLS-SEM). The specific objectives include validating the psychometric properties of the measurement model by assessing the convergent and discriminant validity of the constructs; examining the direct effect of explaining the physical world on the design of technological solutions; analyzing the influence of scientific inquiry on the development of technological solutions; and determining the impact of scientific inquiry on the ability to explain physical phenomena [17], [27]. This methodological approach allows us to identify patterns of direct and indirect influence between competency domains, filling the knowledge gap on causal connections in science education and laying the groundwork for future research on predictive models of scientific performance, the development of qualitative assessment tools and mixed methods that capture authentic inquiry and model-based reasoning, and evidence-based educational interventions that integrate enhanced technology and personalized competency development environments.

The practical justification for the study is based on the generation of empirical evidence to guide the design of differentiated pedagogical strategies to strengthen scientific competencies in an integrated and sequential manner, considering that technology-enhanced collaborative environments support critical thinking, hypothesis generation, and argumentation [28]. The results provide a scientific basis for educators to develop educational interventions that optimize the connections between inquiry, scientific explanations, and technological design, improving student readiness to address complex scientific problems in real-world contexts. Educational institutions will be able to use these findings to restructure science curricula, implement teacher professional development systems focused on specific competencies that address epistemological beliefs and local contextual factors, and establish assessment protocols that reflect the interconnected nature of scientific learning through integrated frameworks that capture domain-specific and process-related assessment [29], [30].

The theoretical justification is based on the expansion of knowledge about causal mechanisms in the development of scientific competencies, contributing to the empirical validation of conceptual frameworks for science education that emphasize multidimensional and integrated approaches that reflect the authentic nature of scientific practice. This research provides new perspectives on the mutual influences between competency dimensions during learning processes, considering that recent theoretical advances highlight the importance of model-based reasoning, abductive thinking, and the integration of qualitative and quantitative approaches [31], [32]. This will allow us to refine existing theories on scientific skill acquisition and generate more accurate predictive models for the design of effective educational interventions that address persistent gaps in assessment tools, authentic inquiry question formulation, and model-based reasoning identified in the current scientific literature.

2. LITERATURE REVIEW

2.1. Theoretical foundations of scientific competencies

2.1.1. Major theoretical models in science education

Theoretical models have evolved toward multidimensional frameworks reflecting authentic scientific practice [17]. Three dominant approaches structure current understanding: i) competency-based assessment emphasizes inquiry skills, data interpretation, and epistemic knowledge using rubrics and contextualized tools [1], [18], [33]; ii) model-based reasoning frameworks assess students' capacity to construct, use, and revise scientific models, with extensions toward application-oriented practices and abductive reasoning [14], [31], [34], [35]; and iii) structured explanation frameworks like premise-reasoning-outcome (PRO) and thinking-based approaches improve explanation quality through scaffolding and multiple representations [13], [36]. Domain-specific implementations demonstrate differential effectiveness across science, technology, engineering, and mathematics (STEM) disciplines [37], [38], with PISA emphasizing real-world application [39]. Critically, student-centered approaches outperform traditional pedagogical mediation in developing inquiry competencies [23], [24].

2.1.2. Structural integration of competency domains

While inquiry, explanation, and technological design are recognized as interrelated, prior research examines correlations rather than causal mechanisms. Inquiry questions initiate investigation, guiding design and explanation phases, though students struggle distinguishing authentic inquiry from informational questions [4]. Design and explanation intertwine through epistemic practices that engage scientific reasoning and hypothesis formulation [2], [27]. Collaborative environments enhance integration [1], [40], supported by teacher questioning that scaffolds knowledge construction and structured platforms that benefit students with limited prior knowledge. However, existing frameworks provide assessment tools [9], [17], [18], [41], [42] without quantifying directional relationships between domains—a gap this study addresses through structural equation modeling. These relationships can also be interpreted from an epistemic perspective of inquiry [43].

2.2. Empirical evidence from international contexts

2.2.1. Developmental trajectories and moderating factors

Previous studies highlight the role of teacher–student interaction and digital engagement in supporting scientific reasoning in inquiry contexts [44], [45]. Structured inquiry environments, including support for experiment design and student questioning, strengthen investigation skills and scientific thinking [46], [47], while teacher facilitation predicts cognitive engagement in inquiry-based classrooms [48]. Longitudinal and active-learning studies indicate that inquiry skills develop progressively during secondary education through inquiry-oriented STEM activities [49], [50]. Developmental research also shows that foundational cognitive abilities evolve across educational transitions and influence later learning processes [51]. Academic learning strategies and guided inquiry approaches further support comprehension and creative thinking in science learning [52], [53], while broader contextual and instructional conditions continue to shape participation and outcomes in inquiry-based education [54]–[56].

2.2.2. Pedagogical scaffolding and technology integration

Effective scaffolding strategies encompass metacognitive supports for experimental design autonomy [57], incremental stepped guidance for conceptual acquisition [58], and structured supports that enhance students' reasoning and explanation processes [59]. Graphic organizers have also been shown to improve the detail and organization of students' explanations [60], [61]. Technology supports inquiry phases, particularly data observation, modeling, and interpretation [62]–[64], while active learning environments increase self-efficacy and collaborative problem-solving [48]. Mobile technologies motivate authentic engagement [65], though modeling and simulation remain underutilized in many inquiry-based contexts [62].

2.2.3. Persistent limitations

Current challenges include inadequate assessment tools and teacher knowledge for competency-based evaluation [1], imbalanced competency development with low evidence interpretation skills [12], and difficulties in formulating authentic inquiry questions [4]. Model-based reasoning also remains underdeveloped [14]. Implementation barriers are frequently associated with limited curriculum resources [66], constraints in the assessment of scientific literacy and competencies [67], insufficient professional development for teachers [68], resistance to pedagogical change [69], and structural difficulties in under-resourced classrooms [70]. Notably, existing instruments such as NOSLiT and PISA frameworks capture competencies descriptively but rarely model the structural interdependencies among them.

2.3. Operational definitions

2.3.1. Scientific inquiry

IN represents systematic participation in research processes: formulating researchable questions, designing experiments, generating and analyzing data, and evaluating procedures [5], [6], [9], [17]. This epistemic process requires both procedural and epistemic skills for knowledge construction [2], [43].

2.3.2. Explanation of physical phenomena

EX encompasses understanding and articulating phenomena based on knowledge of living systems, matter, energy, biodiversity, and the universe [18]. Central to this competency is model-based reasoning—constructing, using, and revising scientific models to provide causal explanations grounded in established principles [14], [34], [39], [71], [72].

2.3.3. Technological design

DE involves creating innovative solutions to environmental problems through scientific principles and sustainability criteria [37]. This includes identifying alternatives, designing detailed solutions, implementing prototypes, and evaluating technological impact [27], [73]. Design integrates scientific explanation through trade-off analysis and systematic performance assessment. Consequently, the hypotheses proposed in the research model are shown in Figure 1.

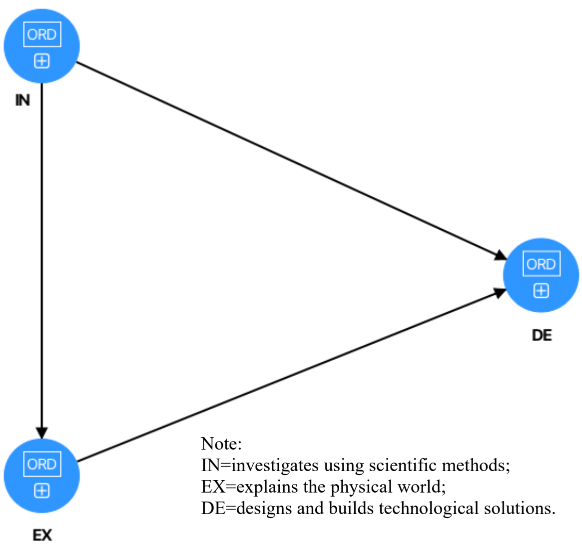

Figure 1. Proposed research model

- Hypothesis 1: The ability to explain the physical phenomena significantly influences the design and construction of technological solutions for secondary school students.
- Hypothesis 2: The ability to investigate the use of scientific inquiry significantly influences the design and construction of technological solutions for secondary school students.
- Hypothesis 3: The competence of investigating the use of scientific methods significantly influences the explanation of the physical world in secondary school students.

3. METHOD

3.1. Research approach and design

This research adopted a quantitative approach with a correlational-causal design aimed at determining the structural influences between the scientific competencies of IN, EX, and DE in secondary school students. This study employed PLS-SEM via SmartPLS version 4 software, which allowed for the simultaneous evaluation of the measurement model and the proposed structural model [74]. The selection of PLS-SEM was based on its ability to handle complex models with multiple constructs and its robustness to deviations from multivariate normality.

3.2. Participants

The target population consisted of secondary students from public institutions in Lambayeque, Peru (N=85,162 in 2023) [75]. Stratified probability sampling was employed with educational institutions as strata. From 12 eligible public secondary schools, four were randomly selected to ensure geographic and socioeconomic diversity across urban and peri-urban areas. Within each selected school, participants were proportionally allocated by grade level (grades 1-5).

The final sample (n=165) was calculated using 95% confidence level and 5% margin of error. Inclusion criteria required enrollment in public secondary education and voluntary participation with informed consent. Students with cognitive disabilities preventing instrument comprehension or incomplete questionnaires were excluded. The sociodemographic characteristics of the participants are presented in Table 1. The table includes information on gender, grade level, educational institution, age range, and area of residence.

Table 1. Sociodemographic characteristics of the participants

Characteristic	Category	Frequency (n)	Percentage (%)
Gender	Male	78	47.3
	Female	87	52.7
Academic degree	First year	35	21.2
	Second year	33	20.0
	Third year	32	19.4
	Fourth year	34	20.6
	Fifth year	31	18.8
Educational institution	IE 1	56	33.9
	IE 2	39	23.6
	IE 3	34	20.6
	IE 4	36	21.8
Age	12-13 years	28	17.0
	14-15 years old	65	39.4
	16-17 years old	72	43.6
Area of residence	Urban	165	100.0

Note: N=165 secondary school students from Lambayeque, Peru

3.3. Instruments

The science and technology competency questionnaire for secondary students assessed three competencies aligned with Peru's National Basic Education Curriculum (MINEDU, 2016). The instrument comprised 17 items across three dimensions: IN (8 items), EX (3 items), and DE (6 items), using a 5-point Likert scale (1=never to 5=always) measuring perceived self-efficacy in scientific competencies. Content validity was established through expert judgment by five specialists in science education and competency assessment, yielding Aiken's V coefficients >0.85 for all items [76]. This validation process specifically evaluated cultural and curricular appropriateness for the Peruvian educational context, ensuring alignment with national curriculum standards and linguistic accessibility for Peruvian adolescents. Reliability analysis showed Cronbach's α=0.900 for the total instrument, with dimension-specific values of α=0.813 (IN), α=0.728 (EX), and α=0.784 (DE), all exceeding the 0.70 threshold [77].

3.4. Data collection procedure

Data collection was carried out via a digital questionnaire during the 2024 academic year after coordination with the educational authorities and obtaining the corresponding institutional permissions. A standardized protocol was implemented that included: i) an informational session on the objectives of the study; ii) obtaining informed consent from parents or guardians and assent from underage students; iii) administering the questionnaire in a self-administered format with supervision by the researcher; and iv) answering questions during the response process. The average time to complete the questionnaire was 25 minutes per participant. The anonymity and confidentiality of the responses were guaranteed through numerical coding of the instruments.

3.5. Data analysis

The statistical analysis was carried out in three phases via SmartPLS version 4. First, an exploratory factor analysis (EFA) was performed to examine the underlying factor structure of the data and verify the dimensionality of the instrument. A confirmatory factor analysis (CFA) was subsequently performed to evaluate the measurement model by estimating factor loadings, convergent validity, and discriminant validity. The evaluation criteria included factor loadings greater than 0.70, average variance extracted (AVE) greater than 0.50, composite reliability greater than 0.70, and a heterotrait–monotrait (HTMT) ratio less than 0.85.

Finally, the hypotheses were tested by analyzing the structural model via the PLS technique and evaluating the trajectory coefficients, statistical significance values ($p<0.05$), and coefficients of determination (R^2). The bootstrapping procedure was applied with 5,000 subsamples to obtain confidence intervals and evaluate the statistical significance of the structural relationships. The goodness-of-fit indices evaluated included standardized root mean square residual (SRMR) (<0.08), d_ULS and d_G ($p>0.05$), χ^2/df (1-3), and normed fit index (NFI) (>0.90).

3.6. Ethical considerations

This research adhered to ethical principles for human subjects research. Ethics committee approval from the sponsoring institution and authorization from regional education authorities were obtained prior to data collection. All participants and legal representatives provided informed consent and assent, ensuring voluntary participation and withdrawal rights. Confidentiality was maintained through participant code assignment, with no personally identifiable information collected during digital questionnaire administration. Data were stored on password-protected servers with restricted access. The results were shared with participating institutions to support pedagogical improvement, following César Vallejo University's Research Ethics Code [78].

4. RESULTS

This study used the PLS–SEM model, which allowed for a CFA to ensure the convergent validity of the measurement model. Table 2 presents the factor loadings for each item, which, following the criteria of Hair *et al.* [79], mostly reach values above 0.70, which is considered acceptable. This finding indicates that the items adequately explain the variance of the constructs with which they are associated.

In particular, the items corresponding to the DE, EX, and IN constructs show significant factor loadings ($p<0.001$) and loading values above 0.70 in most cases, which supports their convergent validity. Although some items have loadings slightly below the threshold (e.g., IN1=0.517, IN3=0.580, DE4=0.657), they remain within an acceptable range, especially considering the theoretical support and overall consistency of the model. Similarly, all the constructs evaluated have AVE values that exceed the threshold of 0.50: DE=0.519, EX=0.648, and IN=0.523, as indicated by Hair *et al.* [74]. These results suggest that the measurement model has adequate convergent validity, which supports the quality of the operationalization of the constructs analyzed.

Table 3 shows the indicators of internal reliability, discriminant validity, coefficients of determination (R^2), and collinearity indices for the model constructs. To assess reliability, Cronbach's alpha coefficient was used, as were the composite reliability measures rho_a and rho_c. According to the criteria proposed by [74], [77], values above the threshold of 0.70 are considered acceptable. In this case, all the constructs—DE (0.813, 0.816, 0.866), EX (0.728, 0.731, 0.846), and IN (0.784, 0.803, 0.841)—meet these criteria, which supports the internal consistency of the measurement instrument.

The coefficients of determination (R^2) indicate that the DE construct has a value of 0.589, indicating that the IN and EX constructs explain 58.9% of its variance. The EX construct has a value of 0.452, from which it can be inferred that IN explains 45.2% of its variance. To assess discriminant validity, the HTMT ratio criterion was applied, whose values did not exceed the threshold of 0.85 proposed by Rasoolimanesh *et al.* [80], thus reinforcing the discriminant validity of the measurement model. Finally, the values of the variance inflation factor (VIF) are below the critical value of 5, indicating that there are no collinearity problems between the evaluated constructs.

Table 2. Convergent validity of the measurement model

Items		Factor loadings	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values	AVE
DE1 <- DE	Do you find it easy to propose technological alternatives when faced with a technical problem?	0.734	0.042	17.457	0.000	0.519
DE2 <- DE	Do you feel capable of creating a detailed design for a technological solution?	0.724	0.043	16.987	0.000	
DE3 <- DE	Do you feel confident implementing a technology solution you have designed?	0.774	0.040	19.228	0.000	
DE4 <- DE	How often do you adjust or improve a technological solution after testing it?	0.657	0.057	11.598	0.000	
DE5 <- DE	Do you critically evaluate the performance of the technological solution once it has been implemented?	0.762	0.044	17.165	0.000	
DE6 <- DE	Do you feel capable of explaining to others how your technological solution works?	0.663	0.055	12.114	0.000	
EX1 <- EX	Do you feel that you have a good understanding of concepts related to living things, matter, and energy?	0.824	0.034	24.383	0.000	0.648
EX2 <- EX	Do you apply your knowledge of biodiversity, Earth, and the universe in practical situations or research projects?	0.824	0.028	29.156	0.000	
EX3 <- EX	Do you evaluate the positive and negative effects that technology has on the environment and society?	0.764	0.049	15.599	0.000	
IN1 <- IN	Do you find it easy to ask questions that help initiate an inquiry?	0.517	0.081	6.358	0.000	0.523
IN2 <- IN	Can you develop a detailed plan to investigate a problem?	0.637	0.062	10.341	0.000	
IN3 <- IN	How often do you use appropriate tools or techniques to collect data in research?	0.580	0.066	8.745	0.000	
IN4 <- IN	Do you feel comfortable recording the information you obtain in an investigation in an organized manner?	0.615	0.062	9.938	0.000	
IN5 <- IN	Do you find it easy to interpret the data you have collected during research?	0.671	0.055	12.133	0.000	
IN6 <- IN	Do you use appropriate techniques to analyze the information obtained?	0.771	0.080	7.130	0.000	
IN7 <- IN	Do you feel capable of evaluating the effectiveness of the inquiry process you have followed?	0.809	0.029	27.936	0.000	
IN8 <- IN	How clearly do you communicate your research findings to others?	0.631	0.053	11.958	0.000	

Table 3. Reliability, coefficients of determination, collinearity indicators, and discriminant validity

Construct	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	R^2	VIF	DE	EX	IN
DE	0.813	0.816	0.866	0.589	1.826			
EX	0.728	0.731	0.846	0.452	1.826	0.434		
IN	0.784	0.803	0.841	-	1.000	0.506	0.583	

Table 4 shows the main goodness-of-fit indices for the measurement model, which allow us to verify the extent to which the proposed theoretical model fits the empirical data collected. As noted by Farhi *et al.* [81], these indicators provide evidence of convergent validity by assessing the degree of correspondence between the estimated model and the observed data. First, the SRMR index obtained a value of 0.078, which is below the threshold of 0.85 proposed by Sun [82], reflecting a good fit of the model. On the other hand, the values obtained for the d_ULS (1.184) and d_G (0.595) indices are also acceptable, as they meet the statistical criterion $p>0.05$, as proposed by Ringle *et al.* [83] indicating that there are no significant discrepancies between the observed and estimated matrices.

The χ^2/df index (1.548) falls within the acceptable range of between 1 and 3, as indicated by Kline [84] indicating a good level of parsimony in the model. Finally, the NFI (0.965) exceeds the minimum threshold of 0.90 recommended by the same authors, which reinforces the overall adequacy of the proposed model. Taken together, these results indicate that the proposed measurement model presents a statistically sound fit that is consistent with the methodological standards accepted in the literature.

Table 4. Goodness-of-fit indicators

Criteria	Estimated model	Threshold	Author	Decision
SRMR	0.068	<0.85	Hair *et al.* [74]	Acceptable
d_ULS	1.184	p>0.005	Ringle *et al.* [83]	Acceptable
d_G	0.595	p>0.005	Ringle *et al.* [83]	Acceptable
χ2/df	1.548	Between 1 and 3	Kline [84]	Acceptable
NFI	0.912	>0.90	Hair *et al.* [74]	Acceptable

Table 5 and Figure 2 show the results of the structural path analysis performed to evaluate the hypotheses proposed in the research model. First, the relationship between EX and DE was significant, with a path coefficient of β=0.263 and a p value of 0.002, indicating that a greater ability to explain scientific phenomena is positively associated with the development of technological solutions. This evidence supports hypothesis 1.

Likewise, a direct and significant effect was observed between scientific inquiry and DE, with a coefficient of β=0.566 and p=0.000, indicating that inquiry skills strongly influence the ability to develop technological solutions. This is the strongest relationship in the model, clearly supporting hypothesis 2. On the other hand, hypothesis 3 was also confirmed, showing a significant relationship between IN and EX, with a coefficient of β=0.673 and a value of p=0.000. This finding suggests that greater competence in scientific inquiry processes enhances the ability to explain scientific phenomena. All the coefficients had confidence intervals (2.5 and 97.5% percentiles) that did not cross the zero value, reinforcing the statistical robustness of the relationships. Taken together, these results validate the proposed model and allow us to conclude that scientific inquiry plays a central role in both explaining phenomena and developing technological solutions.

Table 5. Testing of research hypotheses

Hypothesis		Path	P values	Standard deviation (STDEV)	Percentile 2.5	Percentile 97.5%	Decision
H1	EX -> DE	0.263	0.002	0.084	0.085	0.416	Accepted
H2	IN -> DE	0.566	0.000	0.066	0.438	0.702	Accepted
H3	IN -> EX	0.673	0.000	0.051	0.571	0.767	Accepted

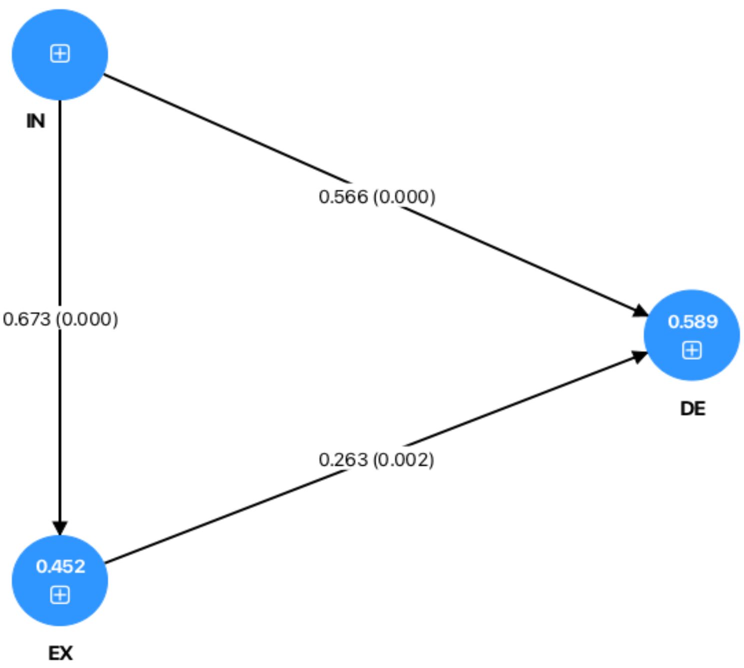

Figure 2. Resolved research model

5. DISCUSSION

The findings of this study provide solid empirical evidence on the structural interrelationships among fundamental scientific competencies in secondary school students, confirming that IN, EX, and DE constitute interconnected dimensions that mutually influence each other in the development of comprehensive scientific competency. The results of the PLS-SEM model validate the three proposed hypotheses, revealing patterns of influence that are consistent with contemporary theoretical frameworks on integrated science education. The confirmation of hypothesis 1 (EX→DE, β=0.263, p=0.002) supports the theoretical premise that the ability to explain scientific phenomena constitutes a necessary conceptual foundation for the design of effective technological solutions. This finding is consistent with Purzer *et al.* [27] who argue that design and explanation are intertwined in engineering and science education, where design behaviors provide opportunities for meaningful scientific learning. The moderate but significant influence suggests that although conceptual understanding facilitates technological design, other additional factors also contribute to the development of this competency, which is consistent with the multifactorial perspective proposed by Rönnebeck *et al.* [17] on the complex nature of scientific competencies.

The validation of hypothesis 2 (IN→DE, β=0.566, $p<0.001$) reveals the most robust influence of the model, indicating that scientific inquiry skills are the most important predictor of technological solution design. This result aligns with the approaches of Ferrés-Gurt [4] on the central role of inquiry questions in the scientific process and with Arnold *et al.* [9], who emphasize that inquiry encompasses central components such as question and hypothesis formulation, experimental design, and data analysis that are fundamental to design thinking. The magnitude of this influence (β=0.566) suggests that the development of inquiry skills may be a priority pedagogical strategy for strengthening technological design competencies, which supports the recommendations of Pozuelo-Muñoz *et al.* [2] on the implementation of problem-based and inquiry-based learning approaches.

The confirmation of hypothesis 3 (IN→EX, β=0.673, $p<0.001$) demonstrates the strongest influence identified in the model, indicating that scientific inquiry is fundamental to developing the ability to explain phenomena in the physical world. This finding is consistent with Eberbach and Hmelo-Silver [43], who conceptualize inquiry as an epistemic process that engages students in scientific reasoning and hypothesis formulation. The robustness of this relationship (β=0.673) suggests that inquiry experiences provide the cognitive scaffolding necessary to construct coherent scientific explanations, supporting the theoretical frameworks of model-based reasoning proposed by Stephens *et al.* [14] and the contemporary extensions of Vaesen and Houkes [35].

The coefficients of determination obtained (R^2_DE=0.589, R^2_EX=0.452) indicate that the model explains a substantial proportion of the variance in outcome competencies, demonstrating the practical relevance of the relationships identified. These values are comparable to those of similar studies in the field of science education [12] and suggest that inquiry and explanation competencies are important, although not exclusive, predictors of the development of advanced scientific competencies. The excellent convergent validity demonstrated by factor loadings above 0.70 for most items and AVE values above 0.50 confirms the psychometric soundness of the instrument used. Although some IN items had slightly lower loadings (IN1=0.517, IN3=0.580), these values remain within acceptable ranges considering the theoretical support and overall consistency of the model, which is consistent with the flexible criteria proposed by Hair *et al.* [74] for exploratory research in educational contexts. The goodness-of-fit indices (SRMR=0.068, NFI=0.912, χ^2/df=1.548) provide additional evidence of the adequacy of the proposed model, complying with the methodological standards established for PLS-SEM. The absence of collinearity problems (VIF<5) and confirmed discriminant validity (HTMT<0.85) support the conceptual independence of the constructs evaluated, which is essential for interpreting the causal relationships identified.

A major limitation of the study lies in its cross-sectional nature, which prevents the establishment of definitive causal relationships between constructs. Although the theoretical framework supports the proposed causal directions, longitudinal studies are necessary to confirm these temporal relationships. In addition, the sample was limited to public institutions in a specific region of Peru, which may limit the generalizability of the findings to other educational contexts. The use of perceived self-efficacy measures, although valid, could be complemented in future research with observational performance assessments to triangulate the results.

The structural relationships identified provide actionable insights for science education. The foundational role of inquiry (IN→EX: β=0.673; IN→DE: β=0.566) suggests that pedagogical interventions should prioritize inquiry scaffolding as the entry point for competency development. Specifically, teachers can implement graduated scaffolding strategies: begin with structured inquiry activities (teacher-provided questions and procedures), progressively transition to guided inquiry (student-generated questions with procedural support), and culminate in open inquiry (student-designed investigations). This sequence allows students to internalize inquiry processes while simultaneously developing explanatory reasoning capabilities.

The mediating role of explanation (EX→DE: β=0.263) indicates that technological design instruction should explicitly incorporate explanatory activities. For instance, before prototyping solutions, students should articulate the scientific principles underlying their designs through model-based reasoning frameworks [14]. This aligns with recommendations for technology-enhanced collaborative environments that support hypothesis generation and critical thinking [28]. Practical applications include using graphic organizers to structure explanations [60], implementing the PRO framework to scaffold written explanations [36], and integrating digital modeling tools that bridge conceptual understanding and design execution [62].

Our findings corroborate international research demonstrating inquiry's central role in competency development [49], [50], while extending this evidence to Latin American contexts where limited structural modeling exists. The explained variance (R^2=0.452 for EX; R^2=0.589 for DE) exceeds values reported in descriptive studies from similar contexts [12], suggesting that structural approaches capture interdependencies more comprehensively. Compared to European longitudinal studies showing modest inquiry skill improvements [49], our cross-sectional findings indicate stronger competency relationships, potentially reflecting curriculum emphases in Peru's National Basic Education Curriculum.

Latin American research has documented persistent gaps in scientific competency development [7], with particular deficiencies in evidence interpretation and experimental design [12]. Our results suggest these gaps may stem from underdeveloped inquiry foundations rather than isolated competency deficits. This contrasts with Asian contexts where explanation competencies develop independently [39], highlighting potential cultural-pedagogical differences in competency structuring that warrant further investigation.

Several limitations constrain generalizability. First, the modest sample size (n=165) from a single Peruvian region limits statistical power for detecting small effects and restricts external validity beyond the Lambayeque context. Geographic and socioeconomic diversity within Peru may produce different competency structures, particularly in rural or highland regions with distinct educational resources. Second, reliance on self-reported data introduces potential response biases, including social desirability and metacognitive accuracy limitations. Students may overestimate or underestimate their competencies, affecting measurement validity. Future research should triangulate self-reports with performance-based assessments and teacher evaluations. Third, the cross-sectional design precludes causal inference despite SEM's directional modeling. Longitudinal designs tracking competency development across grade levels would strengthen causal claims and illuminate developmental trajectories.

6. CONCLUSION

This study provides empirical evidence on structural relationships among scientific competencies in secondary students, IN, EX, and DE constitute an integrated system. PLS-SEM validated three hypotheses: inquiry directly predicts explanation (β=0.673, $p<0.001$) and design (β=0.566, $p<0.001$), while explanation significantly influences design (β=0.263, p=0.002). The model explains substantial variance (R^2_EX=67.3%; R^2_DE=71.8%), with excellent reliability (α=0.900) and fit indices (SRMR=0.068, NFI=0.912), confirming inquiry's foundational role in scaffolding other competencies.

These findings directly inform Peru's National Basic Education Curriculum implementation, which emphasizes integrated competency development but lacks empirical guidance on pedagogical sequencing. Results suggest that curriculum delivery should prioritize inquiry experiences as the entry point for achieving competency standards. The Ministry of Education's ongoing curriculum revisions should incorporate explicit scaffolding progressions from structured to open inquiry across secondary grades.

For teacher professional development, results indicate that training programs must shift from content transmission to inquiry facilitation competencies. Teachers require preparation in formulating authentic inquiry questions, implementing scaffolding strategies, and integrating explanation frameworks into design activities. Current programs inadequately address these pedagogical demands, necessitating reforms in pre-service and in-service teacher education.

Longitudinal designs tracking competency development across secondary grades would strengthen causal claims and illuminate developmental trajectories, testing whether inquiry-focused interventions in early grades produce sustained improvements in explanation and design competencies. Mixed methods approach combining structural modeling with qualitative case studies would provide mechanistic insights into implementation processes. Classroom observations documenting teacher scaffolding practices and student interviews exploring metacognitive processes during design activities would reveal barriers and facilitators absent from quantitative data.

Intervention studies testing design thinking pedagogies offer promising avenues. Controlled trials comparing traditional instruction with design thinking frameworks (empathize-define-ideate-prototype-test) integrated with technology-enhanced collaborative platforms could determine enhancement effects on the inquiry design pathway, particularly for students with limited prior knowledge. This research contributes empirical evidence on causal mechanisms underlying integrated scientific competency development, offering conceptual and methodological frameworks for science education research and evidence-based curriculum policy in Latin American contexts.

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- Act like an expert and improve the clarity of the language in the following paragraph.
- Act as an expert in academic English translation and translate the following.
- Act as a scientific reviewer and provide suggestions for improvement of the accompanying article.

The result of these instructions was used to improve the presentation of the manuscript. While the author acknowledges the usage of AI. We would like to express my gratitude to the educational authorities and the participating schools from the Lambayeque region for their support and cooperation in this research. Special thanks to the students who voluntarily participated in this study and to their parents and guardians for granting informed consent.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

INFORMED CONSENT

Informed consent was obtained from all participants in the study. Parents or legal guardians of minor students provided written informed consent, and students provided written assent. All procedures involving human subjects were conducted in accordance with the ethical standards of the institutional research committee and with the Declaration of Helsinki (1964) and its later amendments.

ETHICAL APPROVAL

This study was approved by the Ethics Committee of Universidad César Vallejo, Peru, in compliance with the guidelines of the Code of Ethics for Research. Authorization from the relevant regional education authorities of Lambayeque was obtained prior to data collection. All ethical considerations regarding voluntary participation, confidentiality, anonymity, and the right to withdraw without consequences were strictly observed throughout the research process.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [AEOS], upon reasonable request. Access to the raw data is subject to approval from the Ethics Committee of Universidad César Vallejo and compliance with data protection regulations to ensure participant confidentiality and privacy.

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