



# Scientific Literacy in Asia: Insights from the Top-Performing Economies in PISA 2022

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## ABSTRACT

*The results reveal that socioeconomic status (ESCS) strongly affects scientific literacy across all five economies, with a particularly pronounced impact in Singapore and Japan. Teacher qualifications, especially the proportion of educators with doctoral degrees, significantly contribute to student performance in South Korea and Chinese Taipei. Additionally, school competition and creative learning environments play varying roles; while Singapore and Macao benefit from structured creativity programs, South Korea's highly competitive environment leads to performance disparities. Psychological factors such as stress resistance and perseverance exhibit mixed effects. In South Korea, stress resistance positively correlates with achievement, whereas in Macao, it negatively impacts performance. Furthermore, student-teacher relationships significantly enhance literacy outcomes in Japan, emphasizing the role of positive academic interactions. These findings highlight the diverse yet interconnected educational strategies driving scientific literacy in Asia's top-performing regions. The study underscores the importance of equitable resource distribution, teacher professional development, and balanced competitive environments in shaping student success. Policymakers can leverage these insights to refine educational frameworks globally, fostering scientific literacy while addressing disparities in STEM education.*

## INTRODUCTION

In the 21st century, scientific literacy is essential for individuals to navigate a rapidly evolving world driven by technological advancements and scientific innovations (Afnan et al., 2023; Li & Guo, 2021; Osborne, 2023). The ability to critically assess scientific information, engage in evidence-based decision-making, and apply scientific principles in daily life is fundamental for personal and societal progress (Jon D. Miller, 2012; Miller, 2022). In response to the increasing demand for STEM-related skills in the global workforce, many education systems worldwide strongly emphasize science education. However, significant disparities exist in students' scientific literacy levels across countries and educational contexts.

The Programme for International Student Assessment (PISA), conducted by the Organisation for Economic Cooperation and Development (OECD), is one of the most comprehensive international assessments of student performance in reading, mathematics, and science. Since its inception in 2000, PISA has provided valuable insights into how education systems prepare students for real-world problem-solving and lifelong learning. As defined by PISA, scientific literacy comprises three core

competencies: explaining phenomena scientifically, evaluating and designing scientific inquiries, and interpreting data and evidence scientifically (OECD, 2019). Given its rigorous methodology and international scope, PISA is a critical benchmark for comparing the effectiveness of science education across countries.

Over the past two decades, Asian countries have consistently outperformed their global counterparts in PISA's scientific literacy domain. In PISA 2022, the five highest-scoring regions—Singapore, Japan, Macao (China), Chinese Taipei, and South Korea—demonstrated exceptional scientific literacy levels, reinforcing the dominance of Asia in STEM education (OECD, 2023). These economies have implemented various educational policies prioritizing rigorous curricula, well-trained teachers, and high academic expectations (Mohamed Anuar & Chankseliani, 2023; Takeuchi et al., 2020). However, despite their high performance, significant differences exist in their educational strategies, cultural influences, and socioeconomic structures.

Existing research on high-performing PISA countries has largely focused on broad cross-country comparisons, often emphasizing overall trends rather than the specific factors driving success in scientific literacy. Previous studies have highlighted the role of educational policies, cultural attitudes, and investment in STEM education in shaping student achievement (Alam & Mohanty, 2023; Wan et al., 2021). However, limited research has systematically examined the interplay between individual and school-level factors in the highest-performing Asian economies. Several key questions remain unanswered. First, there is a need to understand how student characteristics such as socioeconomic status, perseverance, and stress resistance contribute to scientific literacy outcomes. Second, the extent to which school-related factors, including teacher qualifications, school funding, and competition, influence student achievement requires further investigation. Finally, little research has explored the similarities and differences in the determinants of scientific literacy across these five economies. Addressing these questions is critical for understanding high-performing education systems' unique strengths and challenges and identifying best practices that can be adapted globally.

This study aims to bridge the existing research gap by conducting a multilevel analysis of the factors influencing scientific literacy in Singapore, Japan, Macao (China), Chinese Taipei, and South Korea. Using Hierarchical Linear Modeling (HLM), this study systematically examines both individual-level and school-level predictors of student performance. The individual-level factors analyzed include socioeconomic background, psychological traits, and academic perseverance, while the school-level factors include teacher quality, school competitiveness, and resource availability. By employing a quantitative, data-driven approach, this research provides a deeper understanding of how different educational environments foster scientific literacy among students.

The key contributions of this study lie in three main areas. First, it identifies the most influential factors—such as socioeconomic status (ESCS), school resources, and teacher qualifications—that drive scientific literacy in top-performing economies. Second, it offers comparative insights across these five Asian economies, demonstrating that while these regions perform exceptionally well, they adopt different educational strategies that result in varying student outcomes. Third, this study provides evidence-based recommendations for policymakers, particularly in developing countries seeking to improve their STEM education frameworks. By examining the interaction between social, psychological, and institutional factors, this study contributes to a more nuanced understanding of what drives high scientific literacy performance and how these insights can inform global education policies.

## **METHODS**

### ***Data Source***

This study utilizes data from the Programme for International Student Assessment (PISA) 2022, an internationally recognized large-scale assessment administered by the Organisation for Economic Cooperation and Development (OECD). The assessment measures the scientific literacy of 15-year-old students across 81 participating economies, evaluating their ability to explain scientific phenomena, analyze scientific inquiries, and interpret evidence-based data (OECD, 2023). The official PISA 2022 report was published in late 2023, followed by the release of complete datasets, coding manuals, and technical reports in June 2024. This study uses publicly available data from the OECD, ensuring standardized measures for international comparisons.

### Participants and Sampling

The study focuses on students from the five highest-performing economies in the PISA 2022 scientific literacy domain: Singapore, Japan, Macao (China), Chinese Taipei, and South Korea. PISA employs stratified random sampling, selecting students through a two-stage process: first, schools were randomly chosen based on national representativeness, and second, students within these schools were randomly selected. The final sample consists of 29,061 students from the five selected economies, distributed as follows:

**Table 1. Sample Distribution by Country and Gender**

Economy	Female Students	Male Students	Total Sample
Singapore	3,248	3,358	6,606
Japan	2,904	2,856	5,760
Macao (China)	2,140	2,244	4,384
Chinese Taipei	2,852	3,005	5,857
South Korea	3,129	3,325	6,454
<b>Total</b>	<b>14,273</b>	<b>14,788</b>	<b>29,061</b>

In addition to student assessments, principals from participating schools completed school questionnaires, providing institutional-level data on school resources, teacher qualifications, and learning environments.

### Variables and Measurements

This study examines scientific literacy scores as the dependent variable, while independent variables are categorized into individual-level and school-level factors.

**Table 2. Variable Categories and Definitions**

Variable Category	Variable	Description
Individual-Level Factors	Demographic Characteristics	Gender, socioeconomic status (ESCS)
	Psychological Traits	Perseverance, stress resistance, growth mindset
	Social & Emotional Skills	Cooperation, curiosity, emotional control
	School Experience	Student-teacher relationships, sense of belonging
School-Level Factors	Institutional Characteristics	Public vs. private school, school funding
	Teacher Quality	Proportion of teachers with Bachelor's, Master's, or Doctoral degrees
	School Climate	Student-teacher ratio, availability of educational materials, school competition
	Cultural & Extracurricular	Creative activities, beliefs about creativity in education

All variable definitions are derived from the PISA 2022 Student and School Questionnaires ([OECD, 2023](#)).

### **Data Processing and Statistical Analysis**

Before analysis, data cleaning and transformation were performed to ensure data quality. Missing data were addressed using multiple imputations to minimize bias, while outliers were detected and adjusted using winsorization at the 5th and 95th percentiles. Categorical variables (e.g., school type) were transformed into dummy variables, and all continuous predictors were standardized through grand-mean centering to enhance interpretability in the multilevel model.

Given the nested structure of the data (students within schools), Hierarchical Linear Modeling (HLM) was used as the primary statistical technique (Matsuyama, 2020). HLM is preferred over traditional regression methods due to its ability to account for influences on individual and school-level student performance. This model provides three main advantages: (1) it partitions variance between student-level and school-level predictors, (2) it controls for intra-class correlations that arise from clustered data, and (3) it improves estimation precision when analyzing hierarchical data structures. Three models were estimated sequentially to assess model performance: 1. Null Model (Unconditional Model): Estimated the intraclass correlation coefficient (ICC) to determine the proportion of variance explained by school-level factors. 2. Random Intercept Model: Included student-level predictors while allowing school effects to vary. 3. Random Slope Model: Explored whether relationships between student predictors and scientific literacy scores varied across schools. The models were evaluated using the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) to ensure optimal fit.

### **Ethical Considerations**

This study relies on publicly available data from OECD-PISA, which adheres to strict ethical standards regarding data privacy and anonymity. No personally identifiable information was accessed or analyzed. The research complies with international ethical guidelines for secondary data analysis and does not require approval from an additional institutional review board (IRB).

## **RESULTS**

### **Descriptive Statistics: Scientific Literacy Scores in PISA 2022**

This study first examines the descriptive statistics of scientific literacy scores across the five highest-performing economies in the PISA 2022 assessment. Table 3 presents the mean scores, standard deviations, and score ranges for Singapore, Japan, Macao (China), Chinese Taipei, and South Korea.

**Table 3. Comparative Scientific Literacy Scores in PISA 2022**

Country	Mean Score (M)	Standard Deviation (SD)	Min Score	Max Score
Singapore	561.29	95.73	200.10	810.22
Japan	546.22	90.07	256.71	842.50
Macao (China)	543.10	85.21	208.12	768.21
Chinese Taipei	537.47	99.94	138.46	863.27
South Korea	527.66	102.64	52.37	830.75

### **Overall Performance Trends**

The results indicate that Singapore ranks with a mean score of 561.29, maintaining its long-standing position as one of the world's highest performers in scientific literacy. The relatively low standard deviation (95.73) suggests a more homogeneous level of performance among students, indicating that Singapore's education system ensures a high baseline proficiency in science across its student population.

Japan follows with a mean score of 546.22, demonstrating a strong but slightly lower performance than Singapore. Japan's standard deviation (90.07) is the lowest among the five economies, suggesting that students' scientific literacy levels are relatively uniform, with fewer extremely high or low scores. This pattern is consistent with Japan's egalitarian education policies and structured curriculum emphasizing consistent achievement across socioeconomic backgrounds.

Macao (China) ranks third with a mean score of 543.10 and a moderate standard deviation (85.21). The lower variability suggests that Macao's education system is relatively equitable, ensuring that most students reach a comparable level of scientific literacy. Interestingly, Macao's upper score

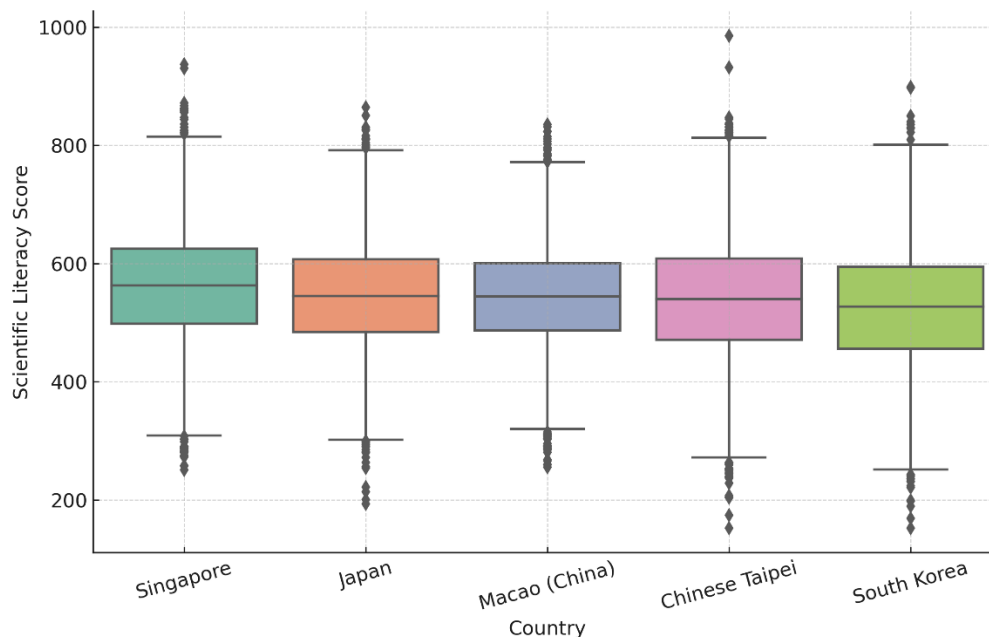
range is slightly lower (768.21) than other high-performing economies, indicating that while its system minimizes low performance, it may not produce as many top achievers as Singapore or Japan.

Chinese Taipei presents a mean score of 537.47, with a higher standard deviation (99.94) than Japan and Macao. It suggests that student performance is more varied, likely reflecting differences in access to educational resources, instructional quality variations, or socioeconomic status disparities. The wide score range (138.46 to 863.27) indicates that while some students excel at an elite level, others perform significantly below the average, making educational inequality a potential concern for policymakers in Chinese Taipei.

While still ranking among the top five globally, South Korea has the lowest mean score (527.66) among the selected economies. It exhibits the highest standard deviation (102.64), with scores ranging from 52.37 to 830.75. It suggests greater variability in student achievement, potentially indicating a highly competitive education system where some students excel while others struggle to keep up. The extreme lower-end scores (52.37) are particularly concerning, as they indicate a subset of students with very low scientific literacy despite South Korea's strong overall educational reputation.

*High vs. Low Performers: Understanding Score Variability*

To further analyze the distribution of performance, Figure 1 presents the score density distribution for each economy, highlighting the spread and concentration of student scores.



**Figure 1. Distribution of Scientific Literacy Scores in PISA 2022**

Singapore and Japan exhibit the most balanced distributions, where most students score close to the mean, indicating that most students achieve a similar level of scientific literacy with relatively few outliers. It suggests that their education systems effectively minimize disparities and provide a uniform learning experience for students.

In contrast, South Korea and Chinese Taipei display wider score distributions, indicating a greater gap between high and low achievers. This pattern suggests that certain student groups excel significantly while others struggle, likely due to disparities in educational access, private tutoring influence, or psychological factors such as academic stress and competition. The extreme score variations in South Korea, in particular, may be attributed to its highly competitive education system, which fosters top-performing students but also results in a subset of students with very low scientific literacy.

Macao (China), on the other hand, exhibits a relatively compressed distribution, meaning that students tend to perform at a more consistent level. It suggests that Macao's education system

successfully ensures educational equity, preventing large disparities between high and low achievers. However, the distribution also indicates that Macao may produce fewer top achievers than other economies, as reflected in the slightly lower upper score range compared to Singapore and Japan.

#### *Gender-Based Performance Differences*

Further analysis reveals gender disparities in scientific literacy performance, which align with global trends observed in previous PISA assessments ([OECD, 2019](#)).

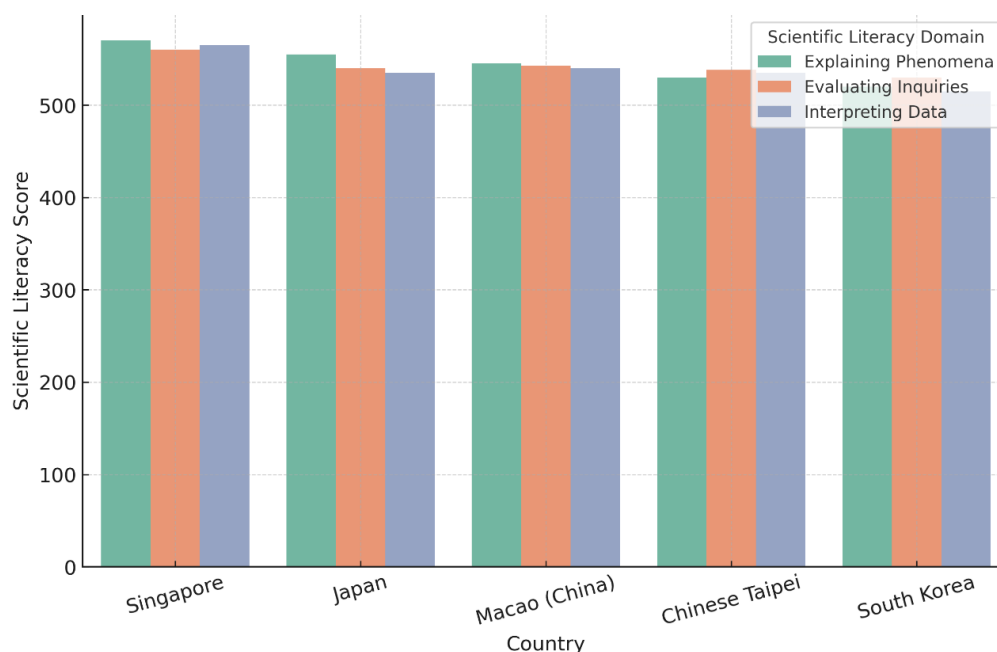
**Table 4. Gender-Based Scientific Literacy Scores**

Country	Female Students	Male Students	Gender Gap (F-M)
Singapore	563.81	558.92	+4.89
Japan	547.93	544.60	+3.33
Macao (China)	544.02	541.87	+2.15
Chinese Taipei	538.10	536.90	+1.20
South Korea	530.45	524.88	+5.57

The results indicate that female students outperform male students in all five economies in scientific literacy, although the gender gap is relatively small. South Korea and Singapore exhibit the largest gender disparities, with female students scoring approximately 5 points higher on average.

#### *Comparative Performance Analysis: Variability and Strengths by Country*

Although the five economies analyzed in this study demonstrate high overall performance in scientific literacy, closer examination reveals distinct patterns of variability and subject-specific strengths across different assessment domains. PISA 2022 evaluates scientific literacy through three key competencies: (1) explaining phenomena scientifically, (2) evaluating and designing scientific inquiries, and (3) interpreting data and evidence scientifically. Figure 2 illustrates the average performance of each economy across these domains, highlighting differences in specific strengths and weaknesses.



**Figure 2. Scientific Literacy Competency Scores by Domain (PISA 2022)**

### *Performance Across Scientific Literacy Domains*

Singapore consistently achieves the highest scores across all three domains, demonstrating a well-balanced proficiency in scientific reasoning. The country's strongest area is Explaining Phenomena Scientifically (570 points), suggesting that students excel in understanding scientific principles and applying them to real-world contexts. Singapore also performs exceptionally well in Interpreting Data and Evidence (565 points), emphasizing data analysis, statistical reasoning, and experimental validation in science education.

Japan follows with a strong performance in Explaining Phenomena Scientifically (555 points), ranking second after Singapore. It suggests that Japanese students have a solid grasp of theoretical concepts and scientific reasoning frameworks. However, Japan scores slightly lower in Interpreting Data (535 points) and Evaluating Scientific Inquiries (540 points), indicating potential gaps in experimental and data interpretation skills compared to Singapore and Macao.

Macao (China) presents a balanced performance across all domains, with scores ranging from 540 to 545 points. This even distribution suggests that students in Macao receive a comprehensive education emphasizing theoretical knowledge, experimental skills, and data interpretation. The minimal variation between domains indicates that Macao's curriculum successfully integrates all aspects of scientific literacy without prioritizing one over the other.

Chinese Taipei performs stronger in Evaluating and Designing Scientific Inquiries (538 points) but slightly lower in Explaining Phenomena (530 points). It suggests that students in Chinese Taipei excel in scientific investigations, hypothesis testing, and designing experiments, aligning with the country's analytical and problem-solving approach to science education. However, the lower performance in scientific explanations indicates that students may require stronger reinforcement in fundamental scientific concepts and principles.

South Korea ranks lowest among the five economies but still performs high. The country demonstrates strong skills in Evaluating and Designing Scientific Inquiries (530 points) but relatively weaker performance in Interpreting Data and Evidence (515 points). The variation in scores suggests that while students possess strong analytical and problem-solving abilities, they may struggle with data-driven decision-making and applied experimentation.

### *Score Variability and Distribution*

Beyond overall performance, the variability of scores within each country provides insights into the distribution of student achievement. Singapore and Japan exhibit relatively low variability, with student scores concentrated around their respective means. It suggests that their education systems minimize disparities and ensure consistent scientific literacy outcomes across diverse student populations. Fewer extreme outliers in Singapore indicate that educational policies and instructional strategies effectively support both high- and low-performing students.

Macao (China) also displays moderate variability, with scores distributed evenly across the student population. It suggests that Macao's education system successfully reduces extreme performance gaps, resulting in a balanced learning environment where students receive equal opportunities to develop scientific literacy skills.

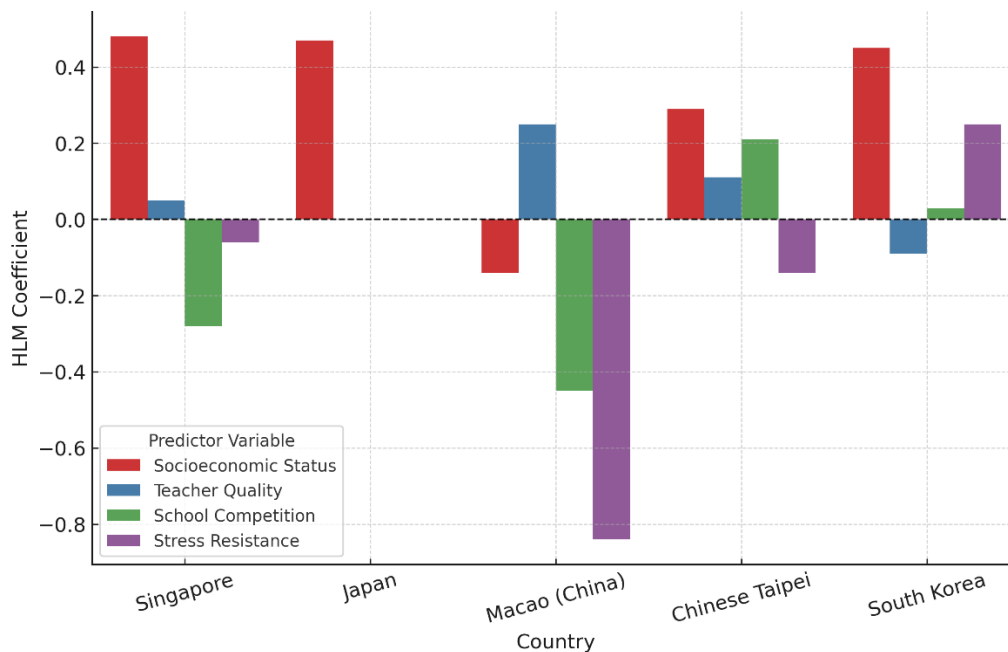
In contrast, South Korea and Chinese Taipei exhibit wider score distributions, indicating a greater gap between top- and low-achieving students. The presence of extreme outliers at both ends of the distribution in South Korea suggests that while some students achieve elite-level performance, others struggle with scientific literacy at a fundamental level. This disparity may reflect differences in educational access, private tutoring influences, or the impact of academic competition on student learning outcomes.

Chinese Taipei also demonstrates higher variability, with scores spanning a wider range. The broader distribution suggests that certain student groups excel significantly while others struggle to master scientific literacy skills. Low-end outliers raise concerns about educational inequality and the accessibility of quality science education across different schools and regions.

### ***Multilevel Analysis: Factors Influencing Scientific Literacy (HLM Results)***

A hierarchical linear modeling (HLM) approach was employed to account for student- and school-level influences and further investigate the determinants of scientific literacy. The results indicate that

socioeconomic status (ESCS), teacher quality, school competition, and psychological factors are among the strongest predictors of student performance across the five highest-performing economies in PISA 2022. Figure 3 presents the standardized regression coefficients for key predictors in each country.



**Figure 3. HLM Regression Coefficients for Key Predictors of Scientific Literacy**

#### *The Impact of Socioeconomic Status (ESCS)*

Socioeconomic status (ESCS) is the most significant predictor of scientific literacy in all five economies. The HLM regression coefficients for ESCS are highest in Singapore (0.48) and Japan (0.47), indicating that students from higher socioeconomic backgrounds consistently achieve better scientific literacy outcomes. It suggests that access to private tutoring, enriched learning environments, and parental educational support are crucial in shaping student achievement in these economies.

In Chinese Taipei (0.29) and South Korea (0.45), ESCS remains an important factor, though with slightly lower coefficients than in Singapore and Japan. The influence of family wealth and educational resources remains substantial but is somewhat mitigated by other factors, such as school-level policies and teacher quality.

Interestingly, Macao (China) shows a negative or non-significant effect (-0.14), suggesting that socioeconomic disparities have a weaker impact on student outcomes. It could indicate that Macao's education system provides equitable access to quality science education, reducing the influence of socioeconomic background on student achievement.

#### *Teacher Quality and Its Role in Scientific Literacy*

Teacher quality, particularly the proportion of educators with advanced degrees (Master's or PhD), has a significant positive impact on student performance in Macao (0.25) and Chinese Taipei (0.11). It suggests that in these economies, higher teacher qualifications contribute directly to better scientific literacy outcomes, likely through improved instructional techniques, better subject knowledge, and enhanced classroom engagement.

In Singapore (0.05), teacher quality shows a weaker but still positive effect, indicating that while teacher credentials matter, other school-level factors, such as curriculum design and resource allocation, play a more dominant role.

Interestingly, in South Korea (-0.09), the relationship between teacher qualifications and student performance is negative. It suggests that having a higher proportion of teachers with advanced degrees does not necessarily translate to better student outcomes, possibly due to rigid teaching methods, standardized curriculum constraints, or misalignment between teacher training and student needs.

### *The Mixed Effects of School Competition*

School competition presents divergent effects across different economies. The coefficient in Singapore (-0.28) and Macao (-0.45) is negative, indicating that higher competition among schools may not always lead to improved student performance. It suggests that excessive academic pressure and ranking-based competition may create stress among students, ultimately reducing their ability to develop scientific literacy skills effectively.

Conversely, in Chinese Taipei (0.21), school competition has a positive impact, suggesting that a controlled level of competition may drive schools to implement higher-quality instructional practices, leading to better student outcomes. The minimal effect in Japan (-0.00) suggests that competition does not significantly shape student achievement in scientific literacy, likely due to the standardized education system and relatively uniform school quality across regions.

In South Korea (0.03), school competition has a small but positive effect, indicating that while competition exists, its influence on scientific literacy is less pronounced than other factors, such as socioeconomic status and student stress levels.

### *The Role of Psychological Factors in Student Performance*

Psychological factors, particularly stress resistance, are highly variable in student performance across different economies. In South Korea (0.25), stress resistance positively correlates with scientific literacy, suggesting that students who can handle academic pressure tend to perform better. Given South Korea's highly competitive education environment, this finding indicates that coping mechanisms and resilience play a crucial role in student success.

In contrast, in Macao (-0.84), stress resistance has a strong negative effect, meaning that students who report high-stress resistance tend to perform worse in scientific literacy. It could indicate that students in Macao who do not feel academic pressure may also lack the motivation to engage deeply in science-related subjects.

The weak or negligible effects in Singapore (-0.06), Japan (0.00), and Chinese Taipei (-0.14) suggest that psychological resilience does not play a major role in shaping student performance in these economies. It may reflect differences in how academic stress is perceived and managed within different cultural and educational contexts.

## **DISCUSSION**

### ***Descriptive Statistics – Scientific Literacy Scores in PISA 2022***

The descriptive statistics of scientific literacy scores in PISA 2022 reveal clear distinctions in student performance across the five highest-performing economies. While all five economies demonstrate strong overall achievement, notable variations emerge in score distribution, equity, and consistency of student outcomes.

Singapore consistently maintains its position as the top performer, reflecting the highly structured and well-resourced education system prioritizing STEM excellence. The relatively low variability in scores suggests that educational policies effectively ensure that most students reach a high level of scientific proficiency, minimizing disparities across different student demographics. It aligns with Singapore's strategic investment in early science education, well-trained teachers, and inquiry-based learning models that foster a deep understanding of scientific concepts ([Le & Edwards Jr., 2023](#); [Tan et al., 2021](#)).

While also excelling in scientific literacy, Japan exhibits a slightly lower overall performance than Singapore but maintains one of the most uniform distributions of scores. It indicates that Japan's standardized national curriculum and strong emphasis on conceptual learning contribute to consistent educational outcomes across diverse student groups. The low variability further suggests that access to quality education is widely distributed, reducing achievement gaps between students from different socioeconomic backgrounds ([Araki, 2025](#); [Lam & Zhou, 2022](#)).

Macao (China) presents a well-balanced performance, with relatively low score variability and stable achievement levels across its student population. It suggests that the education system in Macao is structured to ensure equitable access to quality science education, preventing large disparities in student performance ([Lam & Zhou, 2022](#); [Wei et al., 2022](#)). The country's strong emphasis on well-rounded education, supportive learning environments, and effective classroom instruction likely

contributes to this stability. However, its absence of extremely high-achieving students compared to Singapore and Japan indicates that while equity is achieved, opportunities for elite-level science education might be more limited.

While performing at a high level, Chinese Taipei shows greater variability in student outcomes compared to Singapore and Japan. The presence of top-performing students and lower achievers suggests that educational disparities may exist within the system, potentially influenced by differences in school resources, teacher quality, and access to extracurricular academic support ([Hsieh et al., 2022](#); [Ye et al., 2024](#)). This wider score spread reflects a possible gap between students who benefit from advanced educational opportunities and those who struggle due to limited access to additional academic support.

Despite ranking among the highest globally, South Korea displays the widest score distribution among the five economies. It suggests that while South Korea's education system produces exceptional top achievers, it also has a significant portion of students with lower performance levels. The country's highly competitive academic culture and strong reliance on private tutoring and after-school programs likely contribute to these disparities, as students from more privileged backgrounds may have greater access to supplementary education resources, giving them an advantage over their peers. The presence of students scoring at both the highest and lowest extremes highlights South Korea's challenges in ensuring a more equitable distribution of scientific literacy skills across its entire student population ([Park et al., 2023](#); [Wei et al., 2022](#)).

### ***Comparative Performance Analysis – Variability and Strengths by Country***

The comparative analysis of scientific literacy across the five highest-performing economies in PISA 2022 highlights distinct patterns in how students develop and apply scientific knowledge. While all five economies demonstrate strong outcomes, differences emerge in how well students perform across the three core competencies of scientific literacy: explaining phenomena scientifically, evaluating and designing scientific inquiries, and interpreting data and evidence. These variations reflect deeper structural and pedagogical differences in their education systems, shaping student strengths and overall equity in performance.

Singapore continues to lead in scientific literacy, not only because of its high average scores but also due to its well-balanced performance across all three competencies. The country's education system fosters deep conceptual understanding, data-driven reasoning, and the ability to apply scientific knowledge in real-world contexts. This consistency suggests that Singapore effectively integrates scientific inquiry and problem-solving into its curriculum, ensuring students are equally prepared for theoretical and applied science challenges ([Li & Guo, 2021](#); [Wu, 2025](#)). Its approach is characterized by a structured curriculum, high-quality teacher training, and extensive governmental support for STEM education, which create a learning environment where most students achieve a high level of proficiency.

Japan follows closely behind, excelling particularly in explaining scientific phenomena. It strongly emphasizes conceptual depth and structured reasoning in science education. However, slightly weaker performance in experimental design and data interpretation suggests that while students are highly capable of theoretical understanding, they may have fewer opportunities to engage in inquiry-based learning or hands-on experimentation ([Li & Guo, 2021](#); [Wu, 2025](#)). Japan's highly standardized curriculum and focus on content mastery provide a strong foundation in scientific principles, but the relative gap in applied scientific competencies suggests that additional emphasis on practical scientific investigations may further enhance student performance.

Macao demonstrates a balanced approach, with relatively equal performance across all scientific literacy domains. Its education system appears to provide students with a well-rounded foundation in theoretical and applied science, ensuring that no single competency dominates at the expense of another. Unlike Singapore and Japan, Macao's results do not indicate an exceptionally large proportion of high achievers, suggesting that while students perform well overall, fewer students reach the highest levels of excellence. It may indicate a system prioritizing consistency and general scientific literacy rather than fostering elite performance in STEM fields ([Horta & Li, 2023](#); [Jiang & Zhang, 2024](#)).

Chinese Taipei shows a distinct strength in evaluating and designing scientific inquiries, suggesting that its students are particularly well-trained in scientific investigations, hypothesis testing, and analytical reasoning. This pattern aligns with the country's emphasis on rigorous academic training

and problem-solving, where students are encouraged to approach science education through inquiry-based learning and structured assessments ([Alarcon et al., 2022](#); [Nilimaa, 2023](#)). However, slightly lower performance in explaining scientific concepts suggests that while students excel in analysis and application, they may require additional reinforcement in foundational scientific theories. This discrepancy could point to an education system emphasizing analytical skills but may need further integration of conceptual learning into science instruction.

South Korea presents the most uneven performance across the three domains of scientific literacy. While students are proficient in evaluating scientific inquiries, they show relative weaknesses in interpreting data and evidence, suggesting that while they are adept at structured scientific reasoning, they may struggle with applying those skills in data-driven contexts. South Korea's highly competitive education culture, which strongly emphasizes standardized testing and private tutoring, likely contributes to these patterns ([Jeong & Choi, 2020](#); [Ma, 2023](#)). The system produces many high achievers but also results in significant variability, with some students excelling while others struggle. This discrepancy indicates potential challenges in ensuring that all students receive equal opportunities to develop strong scientific reasoning skills.

Beyond differences in subject-specific strengths, variability in student performance across these economies reveals underlying disparities in educational equity. In Singapore and Japan, student performance is relatively uniform, suggesting that education policies effectively minimize achievement gaps and provide consistent quality across schools. This level of consistency indicates that students from diverse backgrounds have relatively equal access to strong science education, reducing disparities in learning outcomes. In contrast, South Korea and Chinese Taipei display wider score variability, reflecting significant gaps between high and low achievers. These disparities suggest that while some students have access to high-quality resources and additional academic support, others may face barriers that hinder their ability to develop strong scientific literacy skills ([Mulati et al., 2022](#); [Sanders & Wong, 2021](#)).

Macao presents a unique case where performance is relatively balanced, with fewer extremely high achievers and fewer struggling students. It suggests that its education system ensures a stable learning environment for most students, reducing top-end and low-end disparities ([C. W. Lee et al., 2020](#); [Wong et al., 2020](#)). While this approach promotes equity, it may also limit opportunities for the most advanced students to reach elite levels of scientific expertise.

### ***Multilevel Analysis – Factors Influencing Scientific Literacy (HLM Results)***

The multilevel analysis using Hierarchical Linear Modeling (HLM) provides deeper insights into the individual and school-level factors influencing scientific literacy in the five highest-performing economies in PISA 2022. While all five economies exhibit strong overall performance, the factors driving student success vary across different educational contexts. The findings highlight the critical role of socioeconomic background, teacher quality, school competition, and psychological resilience in shaping student achievement.

Socioeconomic status (ESCS) is the strongest predictor of scientific literacy across all economies, confirming the well-established link between family background and educational success ([OECD, 2023](#)). The strength of this relationship varies, with Singapore and Japan showing the highest dependency on ESCS, suggesting that students from wealthier families have significant advantages in accessing quality educational resources, private tutoring, and enriched learning environments ([Debs & Cheung, 2021](#); [Xue et al., 2022](#)). The positive association between South Korea and Chinese Taipei further reinforces that economic disparities translate into academic achievement gaps, where students from privileged backgrounds benefit from better learning opportunities and additional academic support. In contrast, Macao presents a unique case where ESCS has a much weaker effect on scientific literacy, suggesting that its education system provides more equitable access to high-quality learning experiences, reducing the impact of socioeconomic disparities on student performance ([Lo, 2024](#); [Tang, 2022](#)).

Teacher quality, particularly the proportion of educators with advanced degrees, significantly improves student outcomes in Macao and Chinese Taipei ([Chan & Jheng, 2021](#); [J. Lee, 2021](#)). In these economies, higher teacher qualifications contribute to stronger student achievement, likely due to better instructional methods, subject expertise, and engagement strategies that enhance scientific literacy. However, the findings in South Korea reveal an unexpected trend, where teacher qualifications

show no significant or even negative effects on student performance ([M. Lee et al., 2021](#); [Özer, 2020](#)). It suggests that advanced academic credentials alone do not necessarily translate into effective teaching, especially in highly structured education systems where rigid curricula and standardized assessments may limit the flexibility for teachers to apply innovative instructional strategies.

The role of school competition in shaping scientific literacy varies significantly across economies. In Singapore and Macao, higher competition among schools correlates with lower student performance, indicating that excessive academic pressure and ranking-based competition may have counterproductive effects ([Li & Ho, 2024](#); [Rudolf, 2024](#)). These findings suggest that when schools focus too much on high-stakes testing and league tables, students may experience increased stress, reducing their ability to develop deep scientific understanding. In contrast, Chinese Taipei shows a positive association between school competition and scientific literacy, suggesting that moderate levels of competition can drive schools to improve teaching quality and student outcomes ([Creed et al., 2021](#); [Ngoc Diep et al., 2021](#)). This difference in effects highlights that the impact of competition depends on how it is structured within an education system—whether it fosters a productive learning environment or exacerbates student stress and inequality.

Psychological resilience, particularly stress resistance, also shows contrasting effects across economies, revealing important cultural and educational dynamics. In South Korea, students with higher stress resistance tend to perform better, indicating that coping mechanisms and resilience are essential for success in a highly competitive education system ([Choi & Sung, 2024](#); [M. Lee & Lee, 2023](#)). The intense academic environment in South Korea, characterized by long study hours, high parental expectations, and widespread private tutoring, means that only students who can withstand academic pressure excel in scientific literacy. In contrast, Macao presents the opposite trend, where higher stress resistance is associated with lower student performance ([Bellini et al., 2022](#); [Mou & Brito, 2024](#)). It suggests that in education systems where competition is less intense, students who do not feel external academic pressure may also lack motivation or engagement in science-related learning. These findings highlight the complex relationship between student well-being and academic performance, where different cultural attitudes toward stress and competition shape how students approach their education.

## CONCLUSION

This study provides a comprehensive, multilevel analysis of the factors influencing scientific literacy in the top five economies in PISA 2022: Singapore, Japan, Macao (China), Chinese Taipei, and South Korea. Using Hierarchical Linear Modeling (HLM), the findings confirm that socioeconomic status (ESCS) is the strongest predictor of student performance, reinforcing the link between economic advantage and educational achievement. Teacher quality, particularly the proportion of educators with advanced degrees, is crucial, especially in Chinese Taipei and South Korea. School competition's impact varies—while promoting excellence in Singapore and Macao exacerbates performance disparities in South Korea. Additionally, psychological traits such as curiosity, emotional control, and stress resistance show context-dependent effects, with a stronger influence in Macao and South Korea.

These findings highlight key areas for policy intervention to enhance STEM education and reduce disparities. Addressing socioeconomic inequality through targeted financial aid and STEM enrichment programs is critical, particularly in Japan and South Korea. Investing in teacher training and innovative teaching strategies can strengthen student outcomes, particularly in Chinese Taipei. As seen in South Korea, balancing school competition and student well-being is necessary to prevent academic stress from undermining performance. Finally, integrating social-emotional learning into science curricula—such as project-based learning in Macao and stress management programs in South Korea—could enhance student engagement and resilience. Future research should incorporate longitudinal studies and qualitative insights to explore these relationships further and inform evidence-based policy reforms.

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