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The Dual Role of Environmental Literacy and Spatial Intelligence in Developing Students' Ecological Problem-Solving Competencies

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ABSTRACT

Environmental problems such as waste, pollution, climate change, and the depletion of natural resources have exposed the Earth to the threat of extreme global warming. However, students often face difficulties in addressing these issues due to limited involvement in environmental activities and underdeveloped cognitive skills. This study aims to analyze how environmental literacy and spatial intelligence among high school students influence their ability to solve environmental problems. To achieve this, we conducted a questionnaire survey involving 248 students from 11th-grade social science classes. The data were analyzed using Structural Equation Modeling-Partial Least Squares (SEM-PLS) techniques. The findings indicate that: (1) environmental literacy has a significant influence on students' environmental problem-solving ability, with a path coefficient of 0.317 (categorized as good); (2) spatial intelligence also influences problem-solving ability, with a coefficient of 0.422 (good); and (3) the combined structural model of environmental literacy and spatial intelligence shows a stronger influence on problem-solving ability, with a coefficient of 0.590 (categorized as high). Given these findings, it is essential to enhance students' understanding of ecological challenges by improving both their environmental literacy and spatial intelligence. This can be achieved through effective geography learning strategies and by encouraging active student participation in environmental activities. Such a holistic approach is crucial to equip students with the knowledge and skills necessary to address and resolve pressing environmental issues effectively.

Keywords
Ecological Challenges
Environmental Literacy
Environmental Problem-Solving
Spatial Intelligence
Student Involvement

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Introduction

Human life is fundamentally dependent on natural systems; however, various human activities have significantly contributed to environmental degradation, leading to what is increasingly described as environmental crime or "ecocide" [1]. Modern societies face an urgent challenge in transforming traditional patterns of production, consumption, and mobility to mitigate escalating environmental problems. These pressures, intensified by population growth and changing consumption patterns, have resulted in waste accumulation, air pollution, and resource depletion, forming what is known as the triple planetary crisis of climate change, biodiversity loss, and pollution [2].

Climate change represents one of the most critical global environmental challenges. In July 2023, the United Nations declared that the Earth had entered an era of extreme global warming as average global temperatures approached the 1.5 °C threshold established by the Paris Agreement [3]. In Indonesia, environmental issues have become increasingly severe. Temperature anomalies have been recorded in multiple regions, and waste management remains a critical concern. Of the 21.1 million tons of waste generated nationally in 2022, more than 7.2 million tons were inadequately managed [4]. Furthermore, Indonesia is recognized as one of the countries with high levels of air pollution [5].

Addressing these environmental challenges requires educational interventions that extend beyond theoretical understanding. Geography education, when implemented through constructivist and problem-solving approaches, has been shown to equip students with critical thinking and decision-making skills necessary to address ecological problems [6], [7]. Within this context, environmental literacy and spatial intelligence emerge as two essential cognitive domains that may significantly influence students' ecological problem-solving abilities [8].

Environmental literacy encompasses knowledge, attitudes, and behaviors related to environmental sustainability, while spatial intelligence refers to the cognitive capacity to visualize, interpret, and manipulate spatial information [9]. Intelligence plays a central role in problem-solving processes [10]; thus, inadequate development of either environmental literacy or spatial intelligence may hinder students' ability to effectively address ecological issues.

Previous research has demonstrated positive relationships between environmental literacy and environmental problem-solving abilities. Students with low environmental literacy tend to exhibit limited analytical skills and difficulty generating alternative solutions [11]. Similarly, spatial intelligence has been shown to support problem-solving by enabling individuals to process complex spatial data and environmental patterns [12]. However, bibliometric analyses of Scopus-indexed publications from 2013 to 2023 indicate that these constructs are often examined separately, with limited integration in a unified analytical framework.

Therefore, this study aims to analyze the influence of environmental literacy and spatial intelligence on students' ecology-based problem-solving abilities and to identify which factor exerts a more dominant influence. The findings are expected to contribute to theoretical and empirical understanding by proposing an integrated model of environmental literacy, spatial intelligence, and ecological problem-solving within geography education.

Methods

A. Research Method

This study employed a quantitative survey design to examine the relationships between environmental literacy, spatial intelligence, and ecology-based problem-solving abilities among senior high school students. Data were analyzed using Structural Equation Modeling–Partial Least Squares (SEM-PLS), which is suitable for complex models and does not require normal data distribution [13]. For evaluating measurement models and structural models, the Goodness of Fit (GoF) index is used as an overall model fit measure (Equation 1).

$$GoF = \sqrt{Avrg\ Comm\ x\ Avrg\ R^2} \quad (1)$$

B. Population and Sample

The research was conducted in public senior high schools in Bogor City, West Java, Indonesia. Stratified random sampling was applied to select six schools representing different sub-districts. The population consisted of 649 students, and the sample size of 248 students was determined using the Slovin formula with a 95% confidence level. Participants were selected randomly using a digital sampling tool to ensure fairness (Equation 2).

$$n = \frac{N}{1+N(e)2} \quad (2)$$

$$n = \frac{649}{1+649\ (0{,}05^2)} = 248 \quad (3)$$

where:
n: Total samples to be searched
N: Total Population
e: trust value (5%)

The sample was distributed proportionally across schools using Equation 4.

$$n_i = \frac{Ni.n}{N} \quad (4)$$

where:
ni: Total sample to be drawn from each school
n: Total sample
Ni: Total population of each school
N: Total population

To ensure equal opportunity in the selection process, students were chosen using a random lottery method facilitated by the Data Tech Data Sampling Tool. This approach guarantees fairness and randomness in participant selection.

C. Instruments Development

The research instrument consisted of 37 items adapted from established studies and modified to fit the local context while maintaining semantic equivalence [14]. Environmental literacy was measured through indicators of environmental knowledge and attitudes. Spatial intelligence was assessed using indicators of cognitive maps, cognitive collage, and spatial mental imagery. Ecology-based problem-solving ability was measured through indicators of problem definition, identification, alternative solution formulation, and solution selection.

Spatial intelligence and problem-solving abilities were measured using multiple-choice items, while attitudes toward the environment were assessed using a four-point Likert scale, with options such as "always (4)", "often (3)", "sometimes (2)", and "never (1)". For further details, please refer to Figure 1.

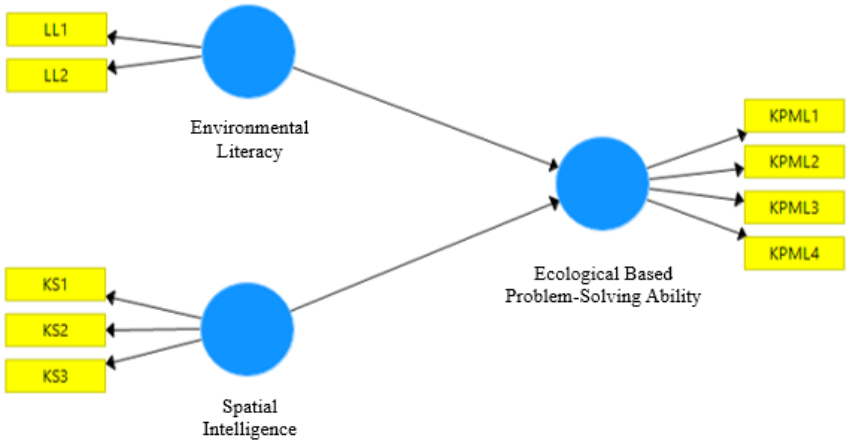


Fig. 1. Proposed Initial Model

where:

LL1: Knowledge Environment
LL2: Attitude To Environment
KS1: Cognitive Maps
KS2: Cognitive Collage
KS3: Spatial Mental
KPML1: Defining the Problem
KPML2: Identify Problem
KPML3: Formulating Alternative Solutions
KPML4: Providing the Best Solution

D. Data analyses

Data analysis followed SEM-PLS procedures using SmartPLS 3 software [14]. The analysis included evaluation of the measurement model (validity and reliability), structural model (path coefficients, R^2, f^2, and Q^2), and hypothesis testing based on t-statistics and p-values with a significance level of 0.05 [15]. The latent variables in this study consisted of exogenous variables such as environmental literacy (X1) and spatial intelligence (X2), and endogenous variables such as ecology-based problem-solving ability (Y). The stages in SEM-PLS analysis are as follows.

1. Outer Model Analysis (Measurement Model): Evaluating the validity and reliability of the indicators used to measure latent variables.
2. Inner Model Analysis (Structural Model): Testing the relationships between the latent variables proposed in the hypotheses.
3. Hypothesis Testing: Using statistical tests to determine whether the proposed hypotheses can be accepted or rejected.

Results

A. Outer Model Test (Measurement Model)

The first step is to evaluate the convergent validity criterion. Convergent validity is an assessment of the suitability of the construct. An indicator is considered to have strong validity when the loading factor has a value of more than 0.70. Even at the model development stage, a loading factor of 0.60 is still considered acceptable [14]. The initial estimation results using the SmartPLS 3 application produce the following calculation output:

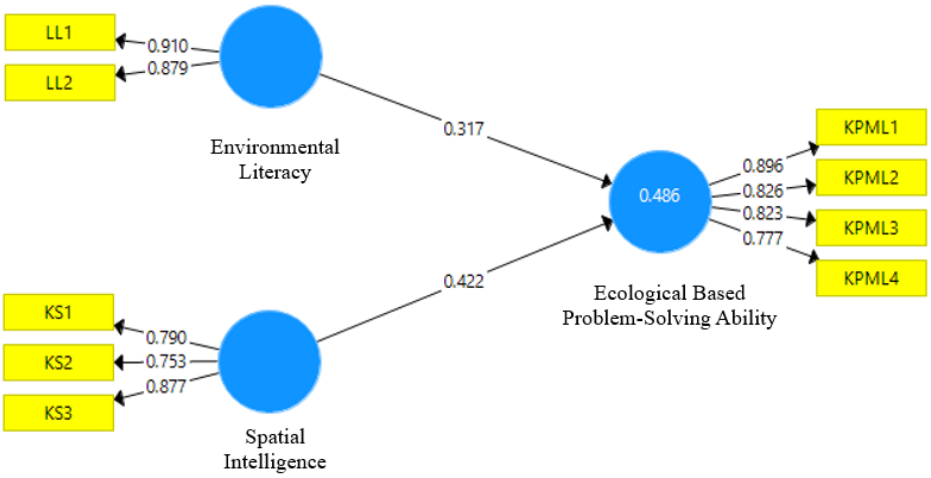


Fig. 2. Loading Factor Value Diagram (Data Processing, 2023)

Based on the test results, it was found that all observed variables showed a loading factor with a value exceeding 0.70. Therefore, the SEM-PLS model is stated to have strong construct validity. Below is a table that shows in detail the loading factor values in the model.

Table 1. Loading Factor

Indicator	Loading Factor	R-critical	Criteria (Loading Factor ≥ 0.7)
LL1 <- Environmental Literacy	0.910	0.7	Valid
LL2 <- Environmental Literacy	0.879	0.7	Valid
KS1 <- Spatial Intelligence	0.790	0.7	Valid
KS2 <- Spatial Intelligence	0.753	0.7	Valid
KS3 <- Spatial Intelligence	0.877	0.7	Valid
KPML1 <- Ecology-Based Problem-Solving Ability	0.896	0.7	Valid
KPML2 <- Ecology-Based Problem-Solving Ability	0.826	0.7	Valid
KPML3 <- Ecology-Based Problem-Solving Ability	0.823	0.7	Valid
KPML4 <- Ecology-Based Problem-Solving Ability	0.777	0.7	Valid

Table 1 presents the factor loading values for each construct derived from the respective variables. From the table, it can be seen that all loading factors have values above 0.7. The next step is to carry out an average variance extracted (AVE) test to strengthen the convergent validity results, with the criterion that the AVE value must be greater than 0.5 (Hair et al. 2019), to confirm the validity of the construct in the research. Table 2 is the results of the average variance extracted test carried out using the PLS 3.0 program.

Table 2. Average Variance Extracted Value

Latent	Average Variance Extracted (AVE)	R critical	Criteria (AVE ≥ 0.5)
Environmental Literacy	0.800	0.5	Valid
Spatial Intelligence	0.653	0.5	Valid
Ecology-Based Problem-Solving Ability	0.692	0.5	Valid

Table 2 shows the results of convergent validity based on the average variance extracted (AVE) value. These data illustrate that each latent variable shows an AVE value that exceeds 0.5. This shows that the indicators that form the latent construct have strong convergent validity based on the average variance extracted.

B. Discriminant Validity Test

This testing process aims to assess the extent of the differences between one construct and another. The discriminant validity test is carried out through Fornell-Lacker criterion analysis, which is a validity test that compares the correlation between variables or constructs with the square root value of the average variance extracted ($\sqrt{AVE}$). An assumption is said to have strong AVE validity if the AVE square root value of each latent variable is greater than the correlation with other latent variables. Table 3 shows the Fornell-Lacker criterion.

Table 3. Fornell-Larcker Criterion

	Spatial Intelligence	Ecology-Based Problem-Solving Ability	Environmental Literacy
Spatial Intelligence	0.808	-	-
Ecology-Based Problem-Solving Ability	0.668	0.832	-
Environmental Literacy	0.775	0.644	0.895

Fornell-Lacker in the criteria analysis for discriminant validity, it can be seen that the root AVE (√) value of each construct exceeds the correlation between each construct and other constructs. One other method used to assess discriminant validity is through cross-loading analysis between indicators and their constructs. This process involves comparing the correlation of indicators to related constructs and the correlation coefficients of indicators to other constructs. The correlation coefficient score between the indicator and the related construct must be higher than the correlation coefficient with other constructs.

C. Reliability Test

Cronbach's alpha and composite reliability are used to evaluate construct reliability. A construct is considered reliable if its Cronbach's alpha and composite reliability exceed 0.70. Although values exceeding 0.60 on Cronbach's alpha and composite reliability can also be considered reliable, below are the results of the reliability test using the Smart PLS 3.0 application.

Table 4. Cronbach's Alpha and Composite Reliability Values

Latent Variables	Cronbach's Alpha	Composite Reliability
Environmental Literacy	0.751	0.889
Spatial Intelligence	0.736	0.849
Ecology-Based Problem-Solving Ability	0.851	0.899

From Table 4, it can be seen that several latent constructs show Cronbach's Alpha values above 0.7, indicating good reliability of these constructs. Most of the latent constructs also show Composite Reliability values above 0.70. From the Cronbach's Alpha and Composite Reliability values, it can be concluded that this model has a good level of reliability.

D. Structural Model (Inner Model)

Inner model evaluation is an analysis of the results of the relationship between constructs. Inner model testing consists of R-squared, F-statistic, and Q-statistic predictive relevance.

1. R Squared

   Furthermore, based on the test results with SmartPLS 3, the R-Squared for the Ecology-Based Problem-Solving Ability variable is 0.486, which means that environmental literacy and spatial intelligence simultaneously influence Ecology-Based Problem-Solving Ability by 48.6%, while the remaining 51.4% is influenced by other variables, which were not examined in this study. R-squared with a value of 0.67 indicates a strong model, a value of 0.33 indicates a moderate model, and a value of 0.19 indicates a weak model [16]. So the R-squared of 0.486 is included in the moderate model.

2. f-Squared

   Next, look at the f-squared value. f-squared for the count of the big influence between variables with an effect size. An f-squared value of 0.02 indicates a small rating, an effect

size of 0.15 indicates a medium rating, and an effect size of 0.35 indicates a large rating [17]. Based on the test results with SmartPLS 3, the following f-squared results were obtained:

Table 5. f-Squared

Variables	Effect Size	Ratings
Ecology-Based Problem-Solving Ability		
Environmental Literacy	0.078	Small
Spatial Intelligence	0.138	Small

3. Q^2 Predictive Relevance

The Q-squared is used to measure how well the observation values produced by the model and the parameter estimates are. A Q-squared value greater than 0 (zero) indicates that the model has predictive relevance, while a Q-squared value of less than 0 (zero) indicates that the model has less predictive relevance [17]. The Q-squared value obtained using the $R2^{value}$ in the table above is as follows:

Table 6. Q^2 Predictive Relevance

Variable	R-Squared	1-R-Squared
Ecology-Based Problem-Solving Ability	0.486	0.514
Q^2	Q^2 = 1- (1-0.486) = 51.4%	
Error	Q^2 = 100% - 51.4% = 48.6%	

Based on the calculation results above, it is known that the value of Q squared is greater than 0. This means that the observed values have been reconstructed well so that the model has predictive relevance. This means that there is 0.514, or 51.4%, of the relative influence of the structural model on the observation measurements for endogenous latent variables, and as much as 48.6% is model error.

4. Hypothesis Test

Hypothesis testing in this research was carried out using the path coefficient, t-value, and p-value. To assess the significance and predictions in hypothesis testing, it can be seen from the path coefficient and t-value with a confidence level of 95% (alpha 5%), two-tailed (1.96). The following t-table values are obtained:

- t-statistic ≥ 1.96: H0 is rejected, and Ha is accepted.
- t-statistic <1.96: H0 accepted and Ha is rejected.

The magnitude of the significance value between the variables being tested is presented in the form of a value in the arrow that connects one variable to the target variable.

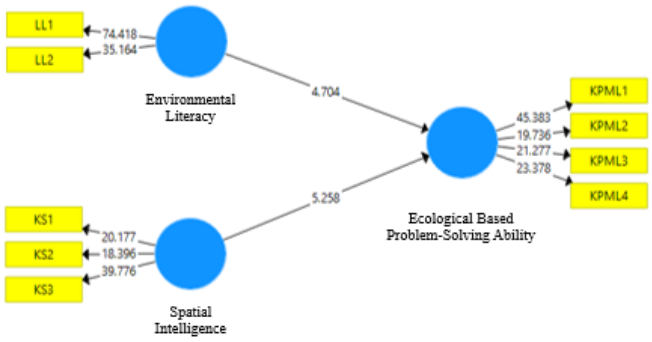


Fig. 3. Significance Value (t-count)

E. Influence Environmental Literacy on Ecology-Based Problem-Solving Ability

The hypothesis was tested using the bootstrapping method with SmartPLS software, and found that the original sample (O) value is 0.317. This value indicates the direction of the positive or parallel influence of environmental literacy on environmental problem-solving abilities, indicating that the higher the environmental literacy, the better the Ecology-Based Problem-Solving Ability. The influence of environmental literacy on environmental problem-solving abilities is proven to be significant, as shown by the t-statistic value of 4.704, which exceeds the value in the t-table (t-table), namely 4.704 > 1.96. In addition, the p-value of 0.000, lower than alpha 5% (0.05), indicates the statistical significance of this effect. Thus, H_1 is accepted, meaning that environmental literacy has a significant effect on environmental problem-solving abilities.

F. The Influence of Spatial Intelligence on Ecology-Based Problem-Solving Ability

Based on the hypothesis that has been mentioned, hypothesis testing was carried out using SmartPLS software, and found that the original sample (O) value is 0.422. This value shows that the direction of influence of spatial intelligence on environmental problem-solving abilities is positive or in the same direction, meaning that the higher the spatial intelligence, the better the environmental problem-solving abilities. The influence of spatial intelligence on environmental problem-solving abilities shows significance, as indicated by the t-statistic value of 5.258, which exceeds the value in the t-table (t-table), namely 5.258 > 1.96. In addition, the p-value of 0.000, lower than alpha 5% (0.05), indicates the statistical significance of this effect. Thus, H_2 is accepted, meaning that spatial intelligence has a significant effect on environmental problem-solving abilities.

G. The Influence of Structural Models of Environmental Literacy and Spatial Intelligence on Ecology-Based Problem-Solving Ability

In evaluating measurement models, structural models, and simple measurements for the overall model predictions using the Goodness of Fit (GoF) test, a GoF value of 0.10 means that

GoF is in the small category; a GoF value of 0.250 means that GoF is in the medium category; and a GoF value of 0.36 means that GoF is in the large category.

Based on the calculation, it is known that the GoF value obtained is 0.590, so it is known that the GoF value is included in the large (high) category. Thus, H_3 is accepted, meaning that the structural model of environmental literacy and spatial intelligence has a significant effect on Ecology-Based Problem-Solving Ability.

Discussion

The hypothesis testing regarding the influence of environmental literacy on ecology-based problem-solving ability shows that environmental literacy has a significant positive effect on environmental problem-solving abilities. This finding indicates that the higher the environmental literacy students possess, the greater their ability to solve environmental problems. This aligns with the other findings [18]-[20], which showed that students with good environmental literacy have better environmental problem-solving abilities, including the ability to analyze solutions carefully and formulate multiple plans. Similar research [21]-[24] supports the influence of environmental literacy and problem-solving abilities. Another study by Lewinsohn et al. [11] corroborates these results by showing that environmental literacy contributes to solving environmental problems, mainly due to its ability to enhance decision-making skills and effective participation in groups responsible for environmental issues.

The research results show that, in terms of knowledge, students' environmental literacy in the path coefficient measurement model falls into the good category with a score of 0.910. This finding is consistent with Aini et al. [25], who found that environmental knowledge is in the good category, influenced by several factors such as the cognitive level of students and the concepts taught by teachers. However, it is important to note that environmental knowledge does not solely depend on formal educational factors but also on other environmental factors such as media information, personal experience, and social influence.

In the context of geography education, understanding the environment, space, geographical factors, human life, and culture is highly relevant in enhancing students' environmental knowledge. It is crucial to emphasize that environmental literacy is not only about mastering information related to environmental issues but also involves practical understanding and application in maintaining environmental sustainability [26]. This aligns with Lee [27], who states that solid knowledge helps students understand and address environmental problems around them.

However, there is a relatively small influence of environmental attitudes in the context of solving environmental problems. This is in line with the findings of Narut et al. [28], who found that the score for attitudes toward the environment tended to be lower compared to the other two subcomponents, knowledge and cognitive skills. Even though students have

knowledge and feelings regarding environmental issues, this is not yet fully reflected in their daily attitudes.

Febriani [29] highlights the weak influence of environmental knowledge and environmental care attitudes. This indicates that the knowledge factor does not necessarily influence students' attitudes. Although students have a good understanding of the environment, they are not fully effective in developing positive attitudes regarding environmental characteristics. This is consistent with the Dual Process Theory, which shows that knowledge (analytical processes) does not always directly influence attitudes toward the environment but is also influenced by concern factors, emotions, experiences, and individual perceptions of the environment (heuristic processes) [30].

One of the factors affecting attitudes toward environmental issues is eco-anxiety. Takshe et al. [31] describe this term as a person's anxiety about the future of themselves, their family, and their children if environmental challenges are not addressed. Although eco-anxiety is often seen negatively, as it can make individuals feel helpless, some studies suggest that awareness of environmental concerns can serve as a driving force for adopting a more positive outlook and motivating attitudes that positively impact the environment [32].

Eco-anxiety highlights the growing concern about the environment in the 21st century, emphasizing that addressing environmental problems requires collective action, not just individual efforts. The concept of Common-Pool Resources (CPRs) or shared resources proposed by Ostrom [33] and the theory of collective action offer an effective solution to environmental issues. This collaborative approach fosters understanding of joint ownership and collective action for the environment.

Active student involvement in addressing environmental problems requires self-confidence and belief in the adequacy of their knowledge [34]. Attitudes toward the environment are also influenced by an understanding of involvement in collective action, which is often acquired through experience [35]. Man et al. [36] show that there are four factors influencing environmental attitudes: (1) systems thinking helps individuals understand the complex relationships in environmental issues; (2) personal reflection on environmental injustice can motivate people to engage in other social and political issues; (3) through action projects, participants can implement their understanding in real-world actions; and (4) role models, peer support, and guidance from experienced activists can help build skills and confidence to engage in environmental activism.

Knowledge plays a vital role in triggering effective actions to address environmental problems. Involving the younger generation in hands-on experiences, active learning, and providing them opportunities to make independent decisions regarding environmental

behavior will be a progressive step in shaping a proactive attitude toward environmental issues [37].

However, as highlighted in previous literature [36], the lack of empirically supported youth engagement programs can hinder long-term involvement in collective action. Participants' lack of connection with local communities and the absence of clear opportunities for engagement hinder sustained involvement. Therefore, there is a need for more structured efforts to provide tangible opportunities for students to contribute to sustainably solving environmental issues.

Fostering an environmental attitude is essential in student education. Learning that emphasizes the importance of caring for the environment is expected to raise students' awareness of the need to attend to nature and the surrounding environment. This view aligns with Kose [38], who emphasized that learning focused on environmental awareness leads to positive changes in students' attitudes toward the environment. Cultivating a caring attitude toward the environment can be achieved through learning activities such as waste sorting, plant care, maintaining classroom and school cleanliness, and other positive habits [39].

A. The Influence of Spatial Intelligence on Ecology-Based Problem-Solving Ability

Hypothesis testing reveals that spatial intelligence significantly influences ecology-based problem-solving ability. This suggests that students with higher levels of spatial intelligence are more capable of effectively addressing complex environmental issues. This finding aligns with previous research by Nurdiono et al. [40], which highlighted a strong correlation between spatial intelligence and problem-solving skills.

Based on the structural model analysis, spatial intelligence exerts a greater influence on ecological problem-solving ability than environmental literacy. This supports the findings of Setiani et al. [41], which emphasize the role of spatial intelligence in processing complex information as an essential component of effective environmental decision-making. Similarly, Urfan [42] noted that intelligence plays a limited role in problem-solving unless supported by sufficient information.

From the perspective of Multiple Intelligences Theory, cognitive abilities such as analytical thinking, creativity, and critical reasoning are key to addressing multifaceted environmental challenges. For example, individuals with high spatial intelligence can design more efficient and sustainable environmental conservation plans by visualizing spatial layouts and simulating future environmental impacts [20].

Additionally, decision-making theory supports the idea that spatially intelligent individuals are better equipped to evaluate environmental consequences and select sustainable alternatives [43]. This ability is especially useful in environmental planning, waste management, urban green space design, and climate change mitigation strategies, where

spatial reasoning plays a crucial role in evaluating land use, risk assessment, and resource allocation.

In practical educational settings, spatial intelligence can be nurtured through geography-based learning activities, such as mapping exercises, field observations, and simulations. These activities encourage students to build cognitive maps, which are mental visualizations of spatial relationships crucial in interpreting environmental phenomena. In this study, students demonstrated a strong ability in the cognitive map aspect, as reflected by a path coefficient score of 0.790. This supports the criteria proposed by Rosyida et al. [44] and conceptualizations by Downs and Stea [9].

Cognitive maps facilitate understanding of spatial dimensions in environmental issues, such as deforestation, urban flooding, and pollution. By mentally mapping affected areas and anticipating changes, students are better able to propose targeted, spatially informed solutions. In the aspect of cognitive collage, students also performed well (score: 0.753). This ability enables them to reconstruct dynamic spatial environments based on past experiences and ongoing interactions [45]. These visual-spatial experiences are essential for forming detailed mental models that aid in environmental analysis and forecasting.

The highest performance was found in the mental spatiality aspect (score: 0.877). As described by Tversky [46], spatial mentality is the most advanced form of spatial intelligence, allowing individuals to simulate environmental processes mentally, anticipate outcomes, and make informed decisions. In this context, spatial intelligence equips students with the tools to become proactive environmental problem-solvers. For instance, when addressing pollution from industrial areas, students with high spatial intelligence can map the affected zones, analyze the flow of pollutants, and propose mitigation strategies that take geographic conditions into account [47].

Geography education thus plays a pivotal role in developing these competencies. As demonstrated in this study, spatial intelligence significantly enhances students' abilities to analyze spatial phenomena, predict future environmental conditions, and design sustainable solutions. This supports Uttal et al. [12].

B. The Influence of Structural Models of Environmental Literacy and Spatial Intelligence on Ecology-Based Problem-Solving Ability

The overall model testing results yield a Goodness of Fit (GoF) value of 0.590, indicating a high level of fit for the proposed model. This result is consistent with previous studies reporting strong model alignment [48], [49]. A high GoF value indicates that the model effectively explains the empirical data and supports its applicability in broader contexts. In SEM-PLS analysis, GoF evaluation is a critical measure of model quality and robustness. Its

flexibility in handling non-normal data enhances the model's reliability in real-world educational research contexts [13].

The structural model illustrates that both environmental literacy and spatial intelligence play pivotal roles in environmental problem-solving. Environmental literacy supports conceptual understanding of ecological systems, while spatial intelligence enhances the ability to visualize and analyze spatial relationships, allowing individuals to propose effective solutions [50], [51].

The interaction between environmental literacy and spatial intelligence provides a comprehensive framework for understanding ecological problem-solving. Problem-solving in environmental contexts requires both conceptual knowledge and spatial reasoning abilities [52]. Therefore, integrating these dimensions within educational curricula is essential for preparing students to address complex environmental challenges effectively.

In conclusion, this study highlights the importance of integrating environmental literacy and spatial intelligence to enhance ecology-based problem-solving abilities. These findings offer valuable insights for curriculum development and educational interventions aimed at strengthening students' competencies in addressing environmental issues.

Conclusion

Environmental literacy positively impacts environmental problem-solving abilities, with a significant influence demonstrated by the coefficient value of 317. Environmental knowledge emerges as a key factor, surpassing attitudes toward the environment in its influence on individual problem-solving skills in environmental contexts. Teaching methods should engage students in multidimensional analyses of environmental issues, including physical, social, economic, and political dimensions. By fostering environmental awareness and concern, geography education can empower students to address global environmental challenges effectively.

Spatial intelligence also plays a vital role in enhancing an individual's ability to solve environmental problems, as indicated by the good coefficient value of 422. Mental spatiality is highlighted as a particularly influential indicator in this regard. This involves adapting learning approaches to focus on enhancing participants' spatial analytical abilities, such as mental mapping and spatial pattern recognition. By integrating spatial intelligence development into geography education, students can acquire the skills necessary to analyze complex environmental problems and devise informed solutions.

The combined model of environmental literacy and spatial intelligence significantly contributes to environmental problem-solving abilities, with a high goodness of fit value of 0.590, indicating strong alignment with empirical data and theoretical frameworks. By incorporating both factors into the curriculum, educators can provide students with

comprehensive learning experiences that combine understanding of environmental issues with spatial analytical skills. This integrated approach equips students with the tools needed to tackle diverse and complex environmental challenges effectively.

Conflict of Interest

The authors declare that there is no conflict of interest.

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