Building Sustainable Futures: Profiling SDGs Understanding and ESD Integration Capacity Among Pre-Service Primary School Teachers

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ABSTRACT

Purpose – This study aims to (1) empirically measure the level of Indonesian pre-service primary school teachers' knowledge of Sustainable Development Goals (SDGs), (2) analyze variations in knowledge levels based on demographic and academic characteristics, and (3) statistically examine the relationship between SDG knowledge levels and pre-service primary school teachers' ability to integrate Education for Sustainable Development (ESD) into science learning.

Methodology – This study employed a quantitative descriptive, cross-sectional design. Empirical data were collected through a survey of 190 pre-service primary school teachers from 21 universities across Indonesia, selected through purposive sampling based on their completion of science education coursework. The research instrument was a 30-item SDG knowledge questionnaire. Data analysis involved descriptive and inferential statistics, including subgroup comparisons and the Chi-Square test of independence.

Findings – The empirical findings indicate that pre-service primary school teachers' SDG knowledge levels were predominantly in the good-to-very-good category (M = 24.74 out of 30). Variations across demographic and academic subgroups were relatively limited, with higher knowledge levels observed among respondents with science (IPA) and primary education (PGSD) backgrounds. The Chi-Square test revealed a statistically significant relationship between SDG knowledge and the ability to integrate ESD into science learning ($p < 0.05$).

Contribution – This study provides quantitative empirical evidence of Indonesian pre-service primary school teachers' readiness to implement sustainability-oriented science instruction. The findings underscore the importance of systematically integrating SDGs and ESD into teacher education curricula to strengthen future teachers' roles as evidence-based agents of change in advancing sustainable primary science education.

INTRODUCTION

Sustainable development has become an urgent global issue in the twenty-first century, driven by escalating challenges such as climate change, environmental degradation, social inequality, and poverty. In response to these pressing problems, the United Nations (UN) introduced the 17 Sustainable Development Goals (SDGs), which aim to create a more equitable and sustainable world by 2030 (Alcántara-Rubio et al., 2022; Bilderback, 2024; Veidemane, 2022). One of the central goals of the SDGs is to ensure inclusive and equitable quality education that not only strengthens knowledge and skills but also fosters awareness of the importance of sustainability (Macintyre et al., 2024). Education is therefore positioned as a strategic driver for achieving sustainability outcomes by shaping individuals capable of critical thinking, responsible decision-making, and long-term engagement with global challenges.

Education for Sustainable Development (ESD) has emerged as a key educational approach for translating the SDGs into meaningful learning practices across educational levels, including teacher education programs (Acosta Castellanos & Queiruga-Dios, 2022; Gorski et al., 2023; Kartawidjaja, 2020; Sihombing et al., 2024). ESD extends beyond knowledge transmission by emphasizing sustainability-oriented competencies, values, and dispositions, such as pro-environmental behavior, social responsibility, and ethical awareness. The successful implementation of ESD depends substantially on teachers' conceptual understanding and pedagogical readiness, highlighting the strategic role of teacher education institutions in developing sustainability literacy.

Within formal education, science education represents a particularly relevant domain for ESD integration due to its close relationship with natural systems, environmental processes, and human–environment interactions. Topics such as climate change, renewable energy, biodiversity, and natural resource management provide authentic contexts for embedding SDG concepts, especially in primary education, where foundational perspectives and values are formed. Pre-service primary school teachers are therefore expected to possess sufficient knowledge of SDGs and the ability to integrate ESD principles into science instruction. Empirical studies, however, indicate that many pre-service teachers demonstrate limited understanding of SDGs and experience difficulties translating sustainability concepts into instructional practice (Franco et al., 2020).

Primary school teachers hold a strategic position in embedding ESD within classroom practice, particularly through science learning that can be directly connected to students' everyday experiences. Effective integration of the SDGs in support of ESD requires an adequate level of conceptual knowledge, which must be systematically developed during teacher education. The effectiveness of ESD implementation in science learning is thus closely linked to pre-service teachers' knowledge and readiness. Examining pre-service teachers' understanding of SDGs becomes a critical step in strengthening sustainability-oriented science education at the primary level (Erlina, 2021; Purnamasari & Hanifah, 2021).

Despite growing global attention to sustainability education, teacher education programs at many universities continue to offer limited, fragmented exposure to the SDGs and ESD concepts. Primary School Teacher Education (PGSD) curricula often lack an explicit, systematic integration of sustainability perspectives, leaving future teachers insufficiently prepared to connect the SDGs with science learning. This curricular limitation raises concerns about pre-service teachers' readiness to serve as agents of change in promoting sustainable education, underscoring the need for evidence-based curriculum evaluation and enhancement (Künzli & Ammon, 2020).

Limited knowledge of the SDGs among pre-service teachers has direct implications for the quality of science learning. Teachers with inadequate sustainability literacy may struggle to implement holistic ESD approaches that integrate cognitive, affective, and behavioral dimensions of learning. Science instruction that fails to incorporate sustainability perspectives risks remaining content-focused without fostering sustainability-oriented attitudes and values. Understanding pre-service teachers' SDG knowledge is therefore essential for identifying how sustainability concepts can be effectively embedded within primary science instruction (Chikoko & Moyo, 2020).

Although research on ESD and sustainability education has expanded considerably, empirical studies that specifically examine the SDG knowledge of pre-service primary school teachers remain limited. Existing studies tend to focus on curriculum design, policy analysis, or classroom implementation, while systematic,

data-driven investigations linking pre-service teachers' SDG knowledge to ESD integration in science learning are still scarce. To substantiate this gap, a bibliometric analysis using VOSviewer was conducted on 200 articles published between 2022 and 2025 indexed in Google Scholar (Figure 1). The analysis reveals that, while ESD is strongly associated with learning, sustainability education, and science, research explicitly focused on pre-service teachers occupies a marginal position, as indicated by weak link strength and small node size. No studies were identified that empirically examine pre-service primary school teachers' readiness to integrate ESD into science learning.

This study is strategically positioned to address this research gap by empirically mapping pre-service primary school teachers' SDG knowledge and examining factors influencing their understanding of sustainability. By providing quantitative evidence on pre-service teachers' SDG literacy, the study strengthens the empirical foundation of ESD research in teacher education. The findings are expected to inform curriculum development in PGSD programs and to support a more systematic integration of the SDGs and ESD in primary science education. Strengthening SDG literacy at the pre-service level is essential for ensuring that primary education serves as a robust foundation for achieving long-term sustainability goals (Ferrer-Estévez & Chalmeta, 2021).

The novelty of this study is supported by a bibliometric analysis conducted using VOSviewer. A total of 200 research articles with the keywords "SDGs" and "ESD" were retrieved from Google Scholar for the years 2022–2025. The mapping of relevant studies is presented in Figure 1.
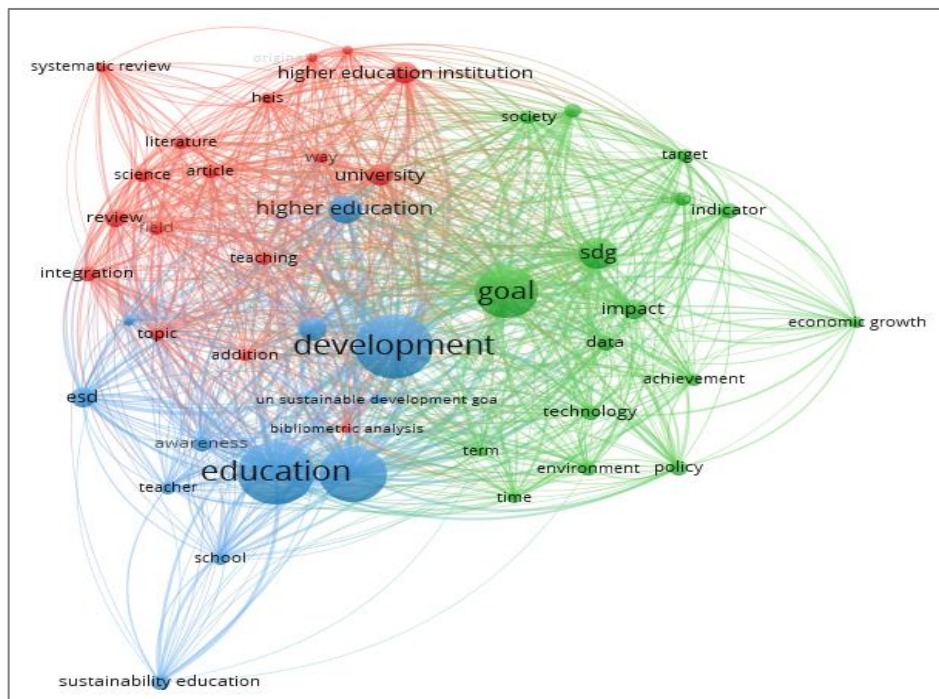

Figure 1. Bibliometric Analysis of Research Novelty

Based on the figure, ESD is strongly connected to topics such as learning, sustainability education, and science, clusters that appear as recent research trends indicated by blue and red clusters. Additionally, the analysis reveals that studies focusing specifically on teachers remain limited. The small node size and the weak visual intensity in the bibliometric network illustrate this. More notably, no studies were found that examined pre-service teachers' readiness to implement ESD. This indicates a clear research gap and highlights the novelty of this study, which maps the SDG knowledge of pre-service primary school teachers to support ESD in science learning.

This research is significant because primary education plays a strategic role in shaping children's worldviews and attitudes toward sustainability. As the initial stage in a learner's educational journey, primary education provides the foundation for understanding sustainability issues that will influence their future lives. By incorporating SDG values into their instruction, pre-service teachers can introduce students to

sustainability concepts relevant to their daily experiences. Consequently, primary education that integrates ESD is expected to produce generations who are more aware of global challenges and capable of contributing to solving increasingly complex environmental and social problems. Therefore, pre-service primary school teachers need adequate knowledge of the SDGs so they can teach and motivate students to become agents of change who care about the future of the planet (Zamora-Polo & Sánchez-Martín, 2019).

METHODOLOGY

Research Design

This study adopted a quantitative descriptive–correlational research design with a cross-sectional approach. The design was explicitly selected to serve two interconnected objectives: (1) to descriptively map the level of Sustainable Development Goals (SDGs) knowledge among pre-service primary school teachers, and (2) to statistically examine the relationship between SDG knowledge levels and their ability to integrate Education for Sustainable Development (ESD) into science learning at a single point in time.

The descriptive component of the design enabled systematic measurement and comparison of SDG knowledge across relevant demographic and academic characteristics, providing an empirical overview of respondents' sustainability literacy. The correlational component allowed for inferential analysis of the association between categorized SDG knowledge levels and ESD integration ability without manipulating variables. A cross-sectional approach was considered appropriate because the study aimed to capture the existing condition of pre-service teachers' knowledge and readiness during their teacher education period, rather than examining developmental changes over time. This integrated design ensures methodological coherence between the stated research objectives, the nature of the data, and the applied statistical analyses.

Participant

The study involved 190 pre-service primary school teachers enrolled in PGSD, PGMI, and PPG-PGSD programs across 21 universities in multiple provinces in Indonesia. Participants were selected using purposive sampling, deemed appropriate given the study's focus on prospective teachers who had already been exposed to science education coursework. The inclusion criteria required participants to: (1) be actively enrolled in a primary teacher education program, (2) have completed at least one course related to science education, and (3) voluntarily consent to participate in the study.

This sampling strategy ensured that respondents had the relevant academic background to meaningfully assess SDG knowledge and ESD integration ability, thereby strengthening the internal validity of the findings. The distribution of participants by province is shown in Figure 2, illustrating the sample's geographical diversity and supporting the study's national-level perspective.
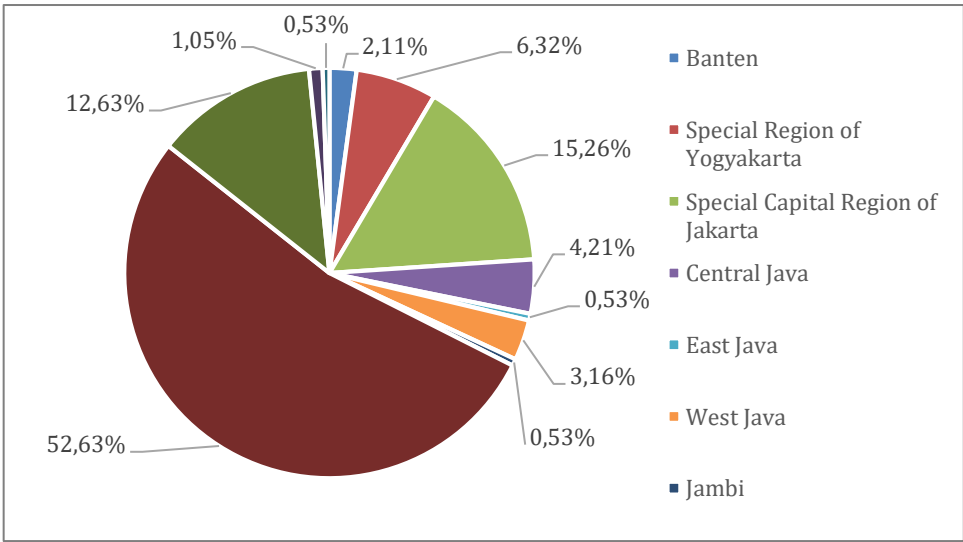

Figure 2. Percentage of Respondents by Province

Demographic Variables

Demographic and academic characteristics—including gender, study program, and provincial origin—were collected as analytical variables rather than merely descriptive information. These variables were selected based on prior research suggesting that differences in educational background, disciplinary orientation, and socio-cultural context may influence sustainability literacy and pedagogical readiness.

Gender was included to explore potential differences in sustainability awareness reported in previous ESD studies. The study program backgrounds (PGSD, PGMI, and PPG-PGSD) were examined to identify variations in SDG knowledge across curricular emphasis and professional training pathways. Provincial origin was analyzed to capture regional differences in access to sustainability-related educational exposure. The inclusion of these variables aligns directly with the study's objective of mapping SDG knowledge profiles and identifying patterns of variation among pre-service teachers, thereby positioning demographic analysis as an integral component of the research design.

Data Collection and Instrument

Data were collected through an online questionnaire administered to eligible participants. Prior to distribution, ethical considerations were addressed by ensuring voluntary participation, confidentiality, and informed consent. Respondents completed the questionnaire independently, and the data were recorded in a secure digital database for analysis.

The research instrument consisted of a 30-item questionnaire developed from five key indicators: (1) basic SDG concepts, (2) the role of teachers in promoting sustainability, (3) the relationship between SDGs and ESD, (4) SDG-oriented science learning activities, and (5) the benefits of integrating SDGs into instruction. All items were measured on a five-point Likert scale (1 = strongly disagree to 5 = strongly agree) to capture respondents' levels of agreement with each statement. Instrument validation was conducted by three experts, resulting in excellent content validity indices (I-CVI = 1.00; S-CVI = 1.00). Reliability testing yielded a Cronbach's Alpha coefficient of 0.757, indicating acceptable internal consistency and strong suitability for assessing SDG knowledge among pre-service primary school teachers.

Data Analysis

Data analysis was conducted using descriptive statistics to determine mean scores, minimum and maximum values, and the distribution patterns of SDG knowledge. Group-based analyses were performed based on gender, provincial origin, and study program to identify variations in knowledge levels. A Chi-Square (x^2) test of independence was employed to analyze the relationship between SDG knowledge levels and the ability to integrate ESD into science learning. The selection of the Chi-Square test was based on the categorical nature of the data, which had been classified into discrete levels, the objective of examining relationships between categorical variables, and the adequate sample size (n = 190). All assumptions of the Chi-Square test were fully met, including independence of observations, presentation of data in contingency tables, and sufficient expected frequencies in each cell, indicating that this test was appropriate and valid for the analysis. All statistical tests were conducted at a significance level of $p < 0.05$.

FINDINGS

Instrument Validation for the SDGs Knowledge Assessment

Before the instrument was used in this study, the researchers asked three validators to assess the appropriateness of each questionnaire item. The validators evaluated the clarity of language, alignment with indicators, content relevance, and the overall suitability of the instrument for measuring students' knowledge of the SDGs. A detailed summary of the validation results is presented in Table 1.

Table 1. Instrument Validation Results for the SDGs Knowledge Assessment

No	Assessment Aspect	Validator		
		I	II	II
1	Alignment of indicators with questionnaire objectives	5	5	4
2	Adequacy of the number of items	5	5	5
3	Clarity of language/formulation	4	5	5
4	Alignment of items with indicators	5	5	5
5	Relevance of content to SDGs & ESD	5	5	5
6	Ability of items to measure declarative knowledge	5	5	5
7	Clarity of instructions	5	5	5
8	Appropriateness of measurement scale format	5	5	5
9	Suitability of the instrument for university students	5	5	5

Based on the results presented in Table 1, the validation scores ranged from 4 to 5. With three validators, the minimum acceptable Item Content Validity Index (I-CVI) is 0.78. The calculated I-CVI was 3/3 (1.00), categorized as "Valid (Excellent)." This was followed by the calculation of the Scale Content Validity Index (S-CVI), which also yielded a score of 1.00, indicating perfect content validity for the SDGs knowledge assessment instrument.

The variance scores for each validator were V1 = 0.055, V2 = 0.000, and V3 = 0.055, yielding a total variance of 0.11 (Var(total) = 0.222). The reliability coefficient (Cronbach's Alpha) was 0.757, indicating consistent and satisfactory reliability. These results demonstrate that the SDGs knowledge assessment instrument is appropriate for use in this study.

General Overview

A general overview of students' SDG knowledge was obtained by calculating descriptive statistics for the collected data. This analysis presents essential information, including mean and maximum scores, minimum and maximum scores, and the distribution of responses. Understanding these descriptive results enables an overall interpretation of participants' knowledge before conducting more detailed analyses of specific groups. The descriptive statistics are displayed in Table 2.

Table 2. Descriptive Statistics

Statistics	Score	Score Conversion
Number of respondents		190
Mean score	24,74	4,12
Minimum score	5,00	0,83
Maximum score	30,00	5,00
Standard deviation	5,85	0,97
Median	27,00	4,50

After gaining an overview of the entire sample, the analysis examined SDG knowledge by gender. The purpose of this analysis was to identify differences between male and female respondents in their understanding of the SDGs. The results include the number of respondents in each gender group, score ranges, mean scores, and their respective categories.

Knowledge of SDGs Among Pre-Service Primary School Teachers in Indonesia

Gender-Based Differences in Pre-Service Primary School Teachers' Knowledge of SDGs and ESD

The findings indicate that the SDG knowledge level of pre-service primary school teachers in Indonesia falls within the good to very good category, with an average score of 24.74 out of 30. This suggests that most

pre-service teachers possess a reasonably comprehensive foundational understanding of the Sustainable Development Goals, including issues related to poverty, education, health, the environment, and global partnerships (Estrada-Araoz et al., 2023; Sharma & Singh, 2023). However, variations in scores were observed across several groups, particularly based on study program, secondary education background, and region of residence. These variations indicate that the quality of SDG understanding is influenced by access to information, institutional curricula, and the socio-educational context that shapes students' competencies (Encabo et al., 2023; Košmerl et al., 2024; Yamano et al., 2022). Overall, these results affirm that pre-service primary school teachers possess strong initial knowledge to support SDG implementation in primary education. However, curriculum reinforcement and equitable access to SDG-related information remain necessary.
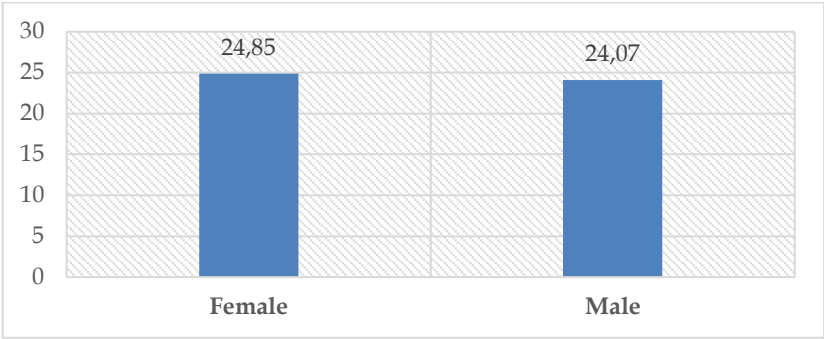

Figure 3. Mean SDGs Knowledge Scores by Gender

The findings based on gender, as illustrated in Figure 3, show that the level of SDG knowledge among pre-service primary school teachers is relatively similar between male and female respondents. The average SDG knowledge score for female respondents is 24.85, while male respondents scored 24.07, with both categorized as "Very Good." This minimal difference indicates that gender is not a significant factor influencing pre-service teachers' understanding of sustainable development concepts. This result aligns with the global literature, which shows that gender differences in sustainability literacy are generally negligible among education students, particularly when access to information and curriculum exposure are relatively equal (Khutkyy & Matveieva, 2024; Lenka, 2023; Presler-Marshall et al., 2022). Thus, the findings reinforce the idea that both male and female pre-service teachers possess comparable cognitive readiness regarding the SDGs, suggesting that other factors, such as academic experience and curriculum exposure, are more likely to influence variations in understanding.

Differences in SDGs and ESD Knowledge Based on Educational Background

The analysis based on students' academic background at the senior high school/vocational school level, shown in Figure 4, reveals more pronounced variations than the gender category. Respondents from the Natural Sciences track scored the highest average (25.72). This can be attributed to the fact that science-track students are generally more exposed to environmental issues, energy, and climate change—topics that are integral to the SDGs. Students from the Social Sciences (IPS) track achieved an average score of 24.26, still within the "Very Good" category. In contrast, other tracks, such as Religious Studies (22.35) and Office Administration (20.83), showed lower averages.

These variations illustrate how understanding of the SDGs is influenced by distinct curricular characteristics at the secondary school level. Science-oriented tracks tend to build stronger foundational knowledge related to sustainability issues (Günther et al., 2022). Nevertheless, the overall "Good to Very Good" rating across most tracks suggests that the SDGs are increasingly recognized across academic fields, though the depth of understanding varies.
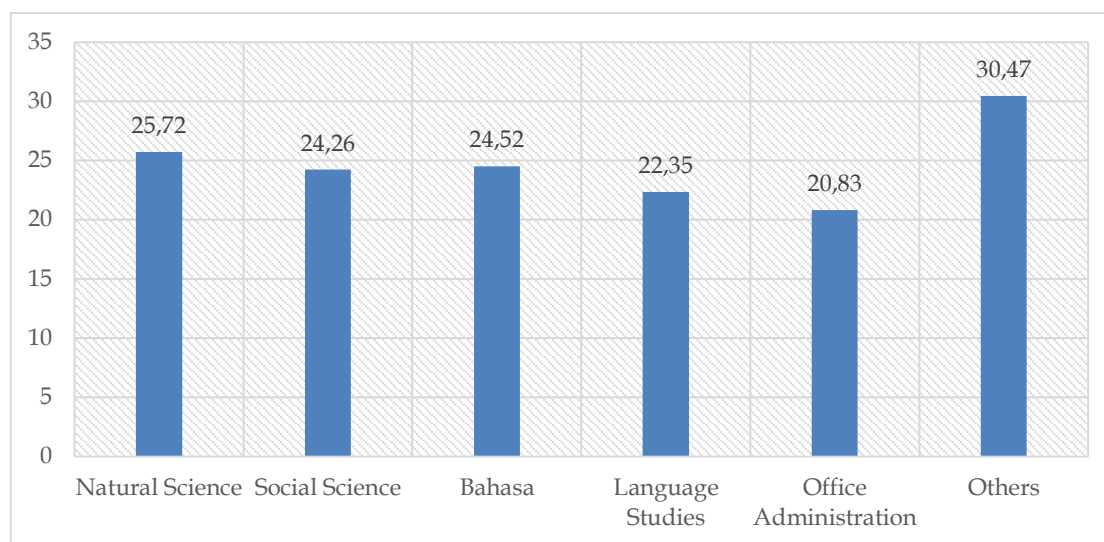
Figure 4. Average SDG Knowledge by High School Academic Background

Differences in SDGs and ESD Knowledge by Study Program

The most prominent differences in SDG knowledge appear when analyzed by study program, as depicted in Figure 5. Students in the PGSD (Primary School Teacher Education) program scored the highest average (25.32), followed by PGMI (Islamic Primary Education) students (23.62). In contrast, participants in the PPG (Teacher Professional Program) obtained the lowest average (18.00). These findings indicate that the undergraduate PGSD program provides more substantial exposure to sustainable education issues through a more comprehensive curriculum, pedagogical coursework, and diverse learning projects.
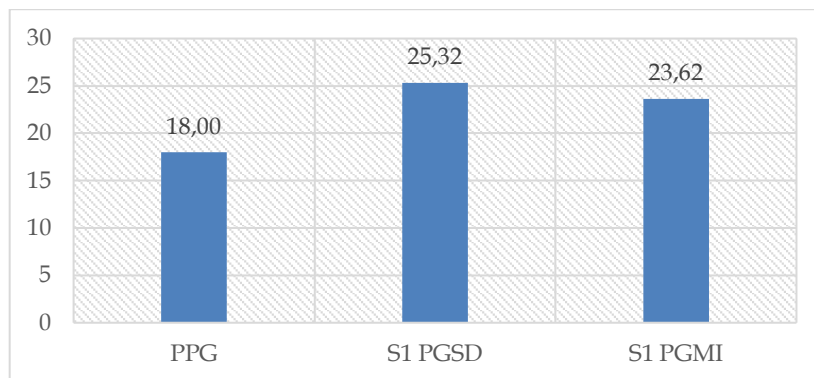

Figure 5. Average SDG Knowledge by Study Program

In contrast, the PPG program—which focuses primarily on professional competency development— tends to offer limited space for explicit SDG content. This aligns with international research demonstrating that pre-service teacher programs with more holistic and extended curriculum structures typically lead to higher SDG literacy compared to shorter professional certification programs (Bermejo et al., 2024; Frank & Ricci, 2023; Martín Bautista-Cerro et al., 2023). Accordingly, these differences highlight the importance of systematically integrating SDGs across all teacher education pathways.

Provincial Differences in Pre-Service Teachers' Knowledge of SDGs and ESD

The provincial analysis in Figure 6 shows variations in SDG knowledge across Indonesia's regions, with most provinces falling into the "Good" to "Very Good" categories. The highest average score is in West Kalimantan (26.20), which is categorized as "Very Good." This may reflect the region's heightened attention to environmental and sustainability issues, as Kalimantan faces significant ecological challenges, including

deforestation and land degradation (Hayati, 2021). Such local contexts often encourage higher education institutions to strengthen sustainability-related coursework.
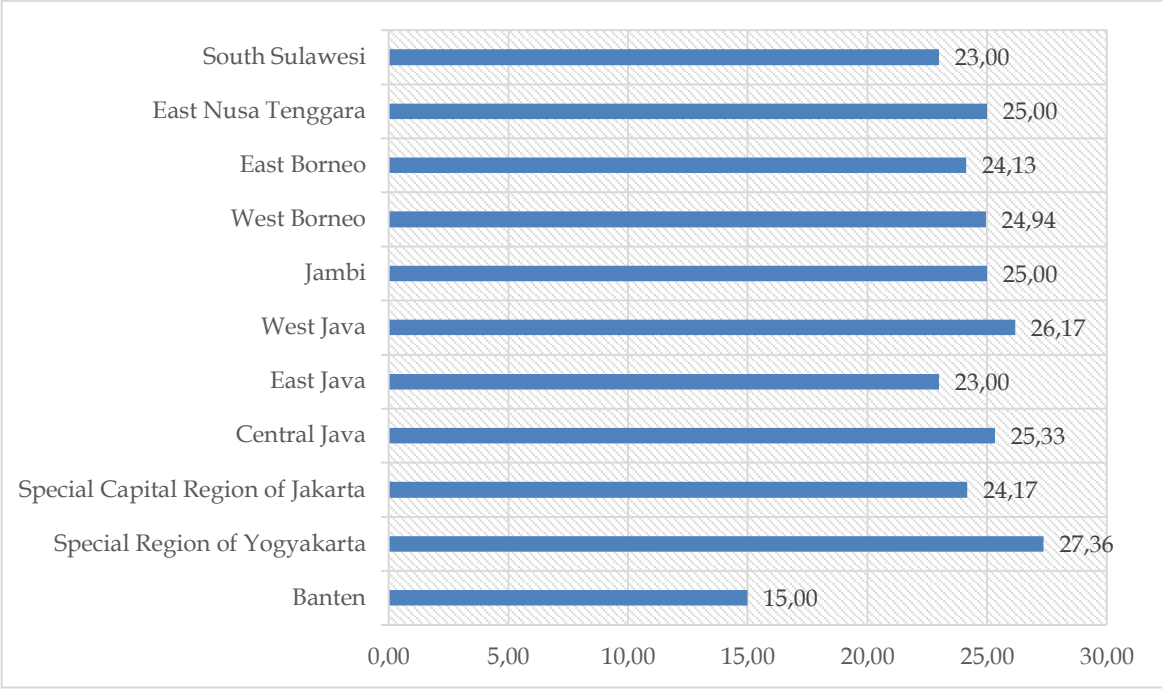

Figure 6. Average SDG Knowledge by Province

Conversely, provinces such as Banten, with an average score of 15.00 ("Fair"), exhibit lower levels of understanding of the SDGs. This lower score may stem from several factors, including variations in institutional curriculum quality, limited integration of SDGs into teacher education courses, or low exposure to sustainability campaigns and environmental issues within the region (Guo et al., 2022; Lim et al., 2022; Zwolińska-Głądys et al., 2022). Differences in social context and institutional characteristics across provinces may also contribute to such variations.

Other provinces, such as West Java (26.17), East Java (23.00), East Kalimantan (24.13), West Kalimantan (24.94), Jambi (25.00), and East Nusa Tenggara (25.00), fall within the "Good" to "Very Good" categories. These relatively high averages indicate that SDGs are fairly well recognized among pre-service teachers in many regions. Contributing factors may include the widespread dissemination of the SDGs in universities, regional government support for environmental education, and the increasing integration of SDG-related material into teacher education programs. Nonetheless, provinces with fewer respondents should be interpreted cautiously due to sampling imbalances. Even so, the overall consistency of scores across regions suggests that access to SDG information is relatively equitable nationwide, aided by digital resources and national policies promoting sustainability education.

Overall, the provincial findings show that SDG knowledge among Indonesia's pre-service primary school teachers is generally strong, with minor regional differences. These variations reflect local contextual factors and the quality of teacher education programs across provinces. Moving forward, efforts to equalize SDG-related curriculum integration are needed to ensure that all pre-service teachers, regardless of region, possess comparable sustainability competencies for implementation in primary education.

Regional (Island-Based) Differences in Knowledge of SDGs and ESD

The distribution of scores by geographic region, presented in Figure 6, shows a relatively consistent pattern, with average SDG knowledge scores ranging from 23 to 25 across most islands. Respondents from Kalimantan recorded the highest average (24.78), followed closely by Nusa Tenggara and Sulawesi (25.00),

and Java (24.66). These minor differences suggest that geographical location does not substantially affect access to SDG information, although some provinces with small sample sizes show lower categories.
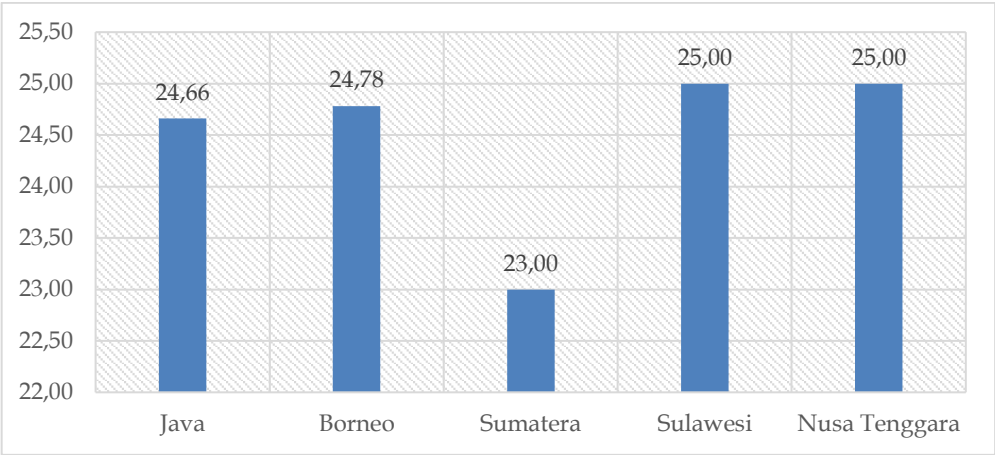

Figure 7. Average SDG Knowledge by Geographic Region

This pattern reflects positive progress in the nationwide dissemination of SDG-related knowledge through digital media, national policies, and environmental education campaigns reaching diverse regions in Indonesia. Nonetheless, the minor variations across regions highlight the need to strengthen further SDG literacy programs, particularly in areas with limited access to education or technology.

Relationship between SDGs Knowledge and ESD Integration Ability

Table 3 presents a contingency table showing the distribution of respondents by their level of SDG knowledge and their ability to integrate ESD into science learning. This analysis aims to examine the relationship between these two variables, specifically to determine whether differences in SDGs knowledge are associated with low or high levels of ESD integration. A Chi-Square test was applied to assess the statistical significance of this relationship and to provide empirical evidence regarding the association between SDGs knowledge and ESD integration ability.

Table 3. Contingency

SDGs Knowledge	Low Integration	High Integration
Low	85	29
High	14	63

Based on Table 3, the Chi-Square test resulted in $\chi^2 = 56.28$ with a p-value of 6.29×10^{-14} (df = 1). This finding indicates a statistically significant relationship between SDG knowledge and the ability to integrate ESD into science learning.

DISCUSSION

Knowledge of Education for Sustainable Development (ESD) among pre-service primary school teachers represents a critical cognitive foundation for implementing science learning that extends beyond conceptual mastery toward the development of ecological, social, and ethical awareness. The present study demonstrates that pre-service teachers' understanding of sustainable development, operationalized through indicators of the Sustainable Development Goals (SDGs), achieved a mean score of 24.74, categorized as "Very Good." This finding indicates not merely descriptive adequacy but also a relatively strong internalization of sustainability concepts that serve as prerequisite knowledge within the ESD competency framework.

From an analytical perspective, the high SDG knowledge score suggests that pre-service teachers possess sufficient conceptual readiness to engage with sustainability-oriented science instruction. Because the SDGs serve as the operational and measurable articulation of ESD principles, SDG knowledge can be interpreted as

a proxy indicator of cognitive preparedness for ESD integration, rather than as isolated factual understanding. This interpretation is consistent with previous empirical studies (Artyukhov et al., 2022; Ceccaroni et al., 2023; Ding et al., 2022; Imrani Tahir & Jafarov, 2023; Jafarov et al., 2023), which emphasize that SDG literacy forms the cognitive gateway through which ESD competencies can be developed in teacher education contexts.

Conceptually, UNESCO's (2017) ESD framework positions knowledge as the first and foundational domain, preceding skills and values. Science learning occupies a strategic role within this framework because its epistemological structure naturally aligns with sustainability issues such as ecosystems, climate change, renewable energy, and human–environment interactions. The findings of this study support this theoretical position by demonstrating that strong SDG-related knowledge equips pre-service teachers with the intellectual resources needed to contextualize science content within real-world sustainability challenges, a core demand of ESD-oriented pedagogy (Castañeda-Garza & Valerio-Urena, 2023; Escobedo et al., 2024).

The observed variation in SDG knowledge across senior high school and vocational education backgrounds further strengthens the analytical contribution of this study. Respondents from science-oriented tracks (MIPA/IPA) achieved the highest scores, indicating that prior exposure to scientific reasoning, environmental concepts, and systems thinking significantly enhances sustainability literacy. This finding reinforces the theoretical argument that ESD knowledge development is cumulative and strongly influenced by prior disciplinary socialization, rather than emerging solely during teacher education. Conversely, lower scores among respondents from non-science backgrounds underscore a structural gap that teacher education programs must address through bridging courses or foundational sustainability modules.

Differences across teacher education programs provide further insight into how institutional curriculum design mediates ESD readiness. Undergraduate PGSD students demonstrated higher SDG knowledge than participants in the PPG program, a difference that can be analytically attributed to differences in curricular orientation and learning duration. Undergraduate programs tend to emphasize conceptual depth, interdisciplinary integration, and educational theory, whereas PPG programs prioritize certification and practical teaching competencies. This finding aligns with Borges and Quintas (2021) and Evans et al. (2017), who argue that the extent to which ESD is integrated depends primarily on curricular structure rather than individual motivation alone. Thus, the present study contributes empirical evidence supporting the claim that ESD competence is institutionally shaped.

Geographical variation in SDG knowledge further highlights the contextual dimension of sustainability education. Provinces with strong academic cultures and supportive educational ecosystems, such as Yogyakarta and West Java, showed higher levels of knowledge. This pattern supports socio-ecological theories of education, which posit that regional policy environments, institutional capacity, and access to sustainability-related discourse shape learning outcomes. The relatively consistent distribution of "Good" to "Very Good" categories across most provinces also suggests that national dissemination of SDG discourse has been effective, although regional disparities persist.

The inferential findings significantly strengthen the empirical and theoretical contribution of this study. The Chi-Square analysis revealed a statistically significant relationship between SDG knowledge and the ability to integrate SDGs into science learning ($\chi^2 = 56.28$; $p < 0.05$). This result confirms that SDG knowledge is not merely descriptive but functionally predictive of pedagogical integration ability. From a conceptual standpoint, this finding empirically validates UNESCO's assertion that knowledge serves as the enabling condition for higher-order ESD competencies, including pedagogical design and instructional decision-making.

Analytically, the strength of this relationship suggests that deficits in SDG knowledge may directly constrain teachers' capacity to translate sustainability principles into instructional practice. Pre-service teachers with higher SDG knowledge are better positioned to identify relevant sustainability issues, align them with science content, and design learning activities that promote systems thinking and problem-solving. This finding corroborates Guo, Huang, and Chen (2024), who emphasize the interplay between content knowledge, pedagogical content knowledge, and sustainability-oriented values in shaping ESD integration.

The contribution of this study lies in its empirical demonstration that cognitive readiness (SDG knowledge) is a key determinant of ESD integration in primary science education. Unlike studies that focus solely on attitudes or self-reported readiness, this research provides statistically grounded evidence linking knowledge levels to instructional capacity. This positions SDG literacy not as an optional enrichment, but as a core component of teacher professional competence.

From a policy and curriculum perspective, the findings underscore the need to embed the SDGs in teacher education curricula systematically. Strengthening SDG literacy through structured coursework, interdisciplinary modules, and contextualized science learning is likely to enhance not only conceptual understanding but also pedagogical action. By doing so, teacher education institutions can better prepare future primary school teachers to serve as agents of change, capable of delivering sustainability-oriented science education that is locally relevant, pedagogically sound, and globally informed.

CONCLUSION

This study provides empirical evidence on the central role of SDG knowledge as a foundational determinant of pre-service primary school teachers' capacity to integrate Education for Sustainable Development (ESD) into science learning. By mapping both the level of SDG understanding and its relationship with ESD integration ability, the findings move beyond descriptive profiling and demonstrate that cognitive mastery of sustainability concepts is significantly associated with instructional readiness for ESD-oriented science teaching. The results confirm that pre-service teachers generally exhibit high levels of SDG knowledge, indicating adequate conceptual preparedness to engage with sustainability issues in educational contexts. More importantly, the statistically significant relationship between SDG knowledge and ESD integration ability highlights that sustainability literacy is not merely an abstract understanding, but a functional prerequisite for pedagogical action. This finding reinforces theoretical perspectives within the ESD competency framework that position knowledge as the enabling condition for the development of pedagogical skills and value-oriented teaching practices. From a scientific contribution standpoint, this study strengthens the empirical foundation of ESD research by quantitatively validating the linkage between SDG literacy and instructional integration ability among pre-service primary school teachers. The findings contribute to the growing body of literature that emphasizes ESD as a competency-based construct, while specifically extending it to the context of primary science education in teacher preparation programs.

The implications of this study are both theoretical and practical. Theoretically, the findings support and operationalize UNESCO's ESD framework by demonstrating how knowledge functions as a gateway to higher-order ESD competencies. In practice, the results underscore the need for teacher education curricula to systematically embed the SDGs and ESD within science education courses, particularly through interdisciplinary content, contextual learning approaches, and sustainability-focused pedagogical training. Strengthening SDG literacy during pre-service education is likely to enhance teachers' capacity to design science learning experiences that are relevant to global challenges while remaining responsive to local environmental and socio-cultural contexts. In conclusion, the study affirms that developing strong SDG knowledge among pre-service primary school teachers is a strategic investment in sustainability-oriented education. When supported by appropriate curricular design and pedagogical training, such knowledge equips future teachers to act as agents of change, fostering scientifically literate, environmentally conscious, and sustainability-aware generations.

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