

Based on Value-Added Assessment: Investigation into the Current Situation of Primary School Students' Scientific Literacy and Dilemma

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Abstract

This study investigates the current situation of primary school students' scientific literacy across 121 schools in Zhejiang Province based on value-added assessment. Findings reveal uneven development across dimensions, with the highest value-added in scientific participation and the lowest in scientific ability. Females outperform males in overall scientific literacy, yet show no significant difference in value-added gains. Rural schools exhibit catch-up potential despite initial lower scores. The study identifies policy implementation discrepancies and resource allocation mismatches, recommending policy optimization, strengthened teacher support, teaching reform, and innovative evaluation systems.

Keywords

Value-Added Assessment, Scientific Literacy, Primary Students, CIPP Model, Educational Equity

1. Introduction

The report of the 20th National Congress of the Communist Party of China emphasized that education, science and technology, and talent constitute the foundational and strategic support for comprehensively building a modern socialist country. In May 2023, the Ministry of Education and other departments issued the Opinions on Strengthening Science Education in Primary and Secondary Schools in the New Era, stressing the importance of enhancing science education

in primary and secondary schools. In 2024, the Overall Plan for Deepening the Reform of Educational Evaluation in the New Era, issued by the CPC Central Committee and the State Council, proposed “exploring value-added assessment” to genuinely achieve the goals of promoting learning and teaching through evaluation.

However, primary school pupils currently exhibit widespread deficiencies in scientific awareness and practical competencies, coupled with inadequacies within the science education evaluation system. There is a pressing need for the implementation of value-added assessment mechanisms that can dynamically track the development of pupils’ scientific literacy.

The objectives of this research are threefold: first, to provide a comprehensive depiction of extant disparities in primary pupils’ scientific literacy across 121 schools in 11 cities of Zhejiang Province through the application of value-added assessment methodologies; second, to undertake a multidimensional examination of the causative factors and influences contributing to challenges in primary science education; and third, to derive evidence-based recommendations for enhancement grounded in the analysis of current conditions and identified challenges.

2. Design and Methodology

2.1. Research Methods

This study adopted a mixed-methods research approach to ensure comprehensive data collection and analysis. The research began with a literature survey method, systematically reviewing existing studies on science education and value-added assessment through databases such as CNKI, using keywords including “primary school science education,” “value-added assessment,” and “scientific literacy” to establish a theoretical foundation.

Subsequently, the questionnaire method was applied to track the value-added trajectory of pupils’ scientific literacy from November 2023 to May 2024 and to examine the impact of multiple variables. Three standardized questionnaires were developed for pupils, parents, and teachers, respectively. The student questionnaire covered basic information and five formal dimensions—scientific concepts, attitudes and emotions, spirit and qualities, participation, and abilities—using a five-point Likert scale. The parent version focused on parental scientific education concepts, involvement, and the student’s learning situation, while the teacher questionnaire assessed environmental foundations, resource allocation, and implementation processes within schools. A mixed mode of paper-based and electronic surveys was employed, conducting two rounds of measurements with the same student cohort to calculate value-added growth based on pre- and post-test differences.

In addition, the in-depth interview method was used to engage school administrators in discussions regarding the foundational environment for science education and the implementation challenges of value-added assessment. Finally, the Delphi method was utilized to gather expert opinions through a multi-round pro-

cess involving expert selection, questionnaire drafting, iterative surveys, and consensus building, with three tailored questionnaires designed for students, parents, and teachers. This study adopted a mixed-methods research approach to ensure comprehensive data collection and analysis.

It is worth emphasizing that in the field of methodological research, more sophisticated alternative value-added assessment models have been widely recognized. These models can handle complex data structures and control potential confounding factors, providing a basis and reference for this study. Two mainstream alternative models are as follows: The Multilevel Model is particularly suitable for educational data with inherent nested structures, such as students nested within classes and classes nested within schools. It can simultaneously quantify variations at multiple levels and isolate the “true value-added effect” of schools or teachers by controlling background variables. The Covariance Model uses pre-test scores as covariates and adjusts initial differences between groups through statistical methods, thereby reducing biases in value-added comparisons. In educational research, Analysis of Covariance (ANCOVA) is often used to compare growth across different groups, with the core being to achieve accurate comparison by controlling baseline performance (McCaffrey et al., 2004).

2.2. Research Object

The research involved a comprehensive survey of participants, including Year 4 and Year 5 pupils in Zhejiang Province’s compulsory education stage, along with their parents, teaching staff, and school administrators. To ensure a representative sample, the study employed stratified cluster sampling, where stratification was conducted based on 11 prefecture-level cities, urban and rural areas, and school types.

Within each stratum, schools were randomly selected to participate. This approach aimed to capture the diversity of economic levels and educational development gradients across Zhejiang Province, thereby minimizing potential bias.

In terms of sample size, the pre-test was conducted in November 2023, distributing a total of 14,000 student questionnaires, 14,000 teacher questionnaires, and 15,000 parent questionnaires.

Valid responses were received from 13,253 students, 1,215 teachers, and 12,356 parents. A subsequent post-test was administered in April 2024, distributing 15,000 student questionnaires, of which 13,253 were validly returned. The valid return rate exceeded 88.0% for both surveys, ensuring robust data for analysis. The final analysis was conducted using data from 13,253 students, their parents, and respective schools.

The significant gap between the 14,000 teacher questionnaires distributed and the 1215 valid ones recovered stems primarily from three practical constraints. First, some questionnaires may have gone unclaimed as they were distributed to teachers unrelated to science education (such as Chinese or mathematics teachers) or were filled out by ineligible personnel, ultimately being deemed invalid during

data cleaning. Second, many teachers abandoned the questionnaires midway due to time constraints or submitted forms with missing key information, rendering them invalid. Finally, the study employed a combination of paper and electronic questionnaires, with insufficient reminders for teachers to submit their responses. Unlike student questionnaires, which were completed under the supervision of class teachers, this further lowered the effective recovery rate.

After validation, the Cronbach's α coefficients were 0.82 for the student questionnaire, 0.78 for the parent questionnaire, and 0.75 for the teacher questionnaire, respectively. This indicates that the questionnaires have good reliability. Results from Exploratory Factor Analysis (EFA) showed that all questionnaires have acceptable construct validity, with the cumulative variance explained for each dimension exceeding 65%.

3. Findings from the Survey on Pupils' Scientific Literacy Based on Value-Added Assessment

3.1. Overall Value-Added Situation of Pupils' Scientific Literacy

Based on the pre-test data, as shown in **Table 1**, the mean score for students' scientific literacy was 4.2557; the mean scores for scientific concepts, scientific abilities, scientific participation, scientific attitudes and emotions, and scientific spirit were 4.1377, 3.8998, 4.4400, 4.7180, and 4.0828 respectively. Among these, scientific abilities had the lowest mean score, whereas scientific attitudes and emotions received the highest.

Table 1. Descriptive analysis of pre-test results of students' scientific literacy.

Dimension	N	Minimum	Maximum	Mean	Std. Deviation
Scientific Concepts	13,253	2.25	5.00	4.1377	0.69840
Scientific Ability	13,253	1.57	5.00	3.8998	0.71971
Scientific Participation	13,253	2.00	5.00	4.4400	0.67649
Scientific Emotional Attitude	13,253	1.00	5.00	4.7180	0.49567
Scientific Spirit	13,253	1.57	5.00	4.0828	0.79952
Overall Mean	13,253	2.39	5.00	4.2557	0.36839
Valid N (listwise)	13,253				

Analysis of the mean differences between pre-and post-tests reveals, as shown in **Table 2**, that the overall value added for student scientific literacy ranged from a minimum of -0.86 to a maximum of 1.18 , with a mean of 0.2116 . The mean gains for scientific concepts, scientific abilities, scientific participation, scientific attitudes and emotions, and scientific spirit were 0.1871 , 0.1152 , 0.3707 , 0.2538 , and 0.1312 respectively. Scientific participation demonstrated the greatest gain, while scientific abilities showed the smallest. Analysis in conjunction with pre-test data indicates that students' scientific abilities are not only relatively low but also exhibit slower growth.

Table 2. Descriptive analysis of value-added in students' scientific literacy.

Dimension	N	Minimum	Maximum	Mean	Std. Deviation
Scientific Concepts	13,253	-0.63	0.63	0.1871	0.32328
Scientific Ability	13,253	-0.50	0.67	0.1152	0.31669
Scientific Participation	13,253	-1.71	1.86	0.3707	0.88938
Scientific Emotional Attitude	13,253	-1.75	2.50	0.2538	0.90496
Scientific Spirit	13,253	-0.71	0.86	0.1312	0.42407
Overall Mean	13,253	-0.86	1.18	0.2116	0.30756
Valid N (listwise)	13,253				

3.2. Differences in Science Literacy Value-Added among Student Groups

Through mean tests and independent samples t-tests on the pre-test data for overall scientific literacy and its dimensions across different genders, as shown in **Table 3**, female students significantly outperformed male students in overall scientific literacy and sub-dimensions except scientific concepts. No significant difference existed between male and female students in the scientific concepts dimension.

Table 3. Descriptive analysis of value-added in students' scientific literacy.

Mean	Male (N = 6799)		Female (N = 6454)		t
	Mean	SD	Mean	SD	
Scientific Concepts	3.6816	0.82637	3.6779	0.81148	0.157
Scientific Ability	4.3669	0.68830	4.5199	0.59208	-8.513***
Scientific Participation	4.2752	0.63569*	4.4357	0.57034	-9.178***
Scientific Emotional Attitude	4.0566	0.57761	4.1012	0.55889	-2.798**
Scientific Spirit	4.1834	0.68712	4.2955	0.62166	-6.109***
Overall Mean	4.0743	0.51600	4.1592	0.47548	-6.107***

Through mean tests and independent samples t-tests on their gains, as shown in **Table 4**, no significant gender differences were found in gains across all dimensions of scientific literacy.

Table 4. Descriptive analysis of value-added in students' scientific literacy.

Mean	Male (N = 6799)		Female (N = 6454)		t
	Mean	SD	Mean	SD	
Scientific Concepts	0.1869	0.32700	0.1872	0.31946	-0.031
Scientific Ability	0.1109	0.31760	0.1202	0.31539	0.293
Scientific Participation	0.3812	0.89160	0.3605	0.88976	0.830
Scientific Emotional Attitude	0.2498	0.88122	0.2537	0.92922	-0.155
Scientific Spirit	0.1334	0.42528	0.1278	0.423428	0.468

Through mean tests and independent samples t-tests on the pre-test results for overall scientific literacy and its dimensions among Year 4 and Year 5 pupils, as shown in **Table 5**, significant differences exist between Year 4 and Year 5 in both overall scientific literacy and its sub-dimensions, with Year 5 pupils consistently outperforming Year 4 pupils.

Table 5. Analysis of pre-test scientific literacy results across year groups.

Mean	Grade 4 (N = 6467)		Grade 5 (N = 6786)		t
	Mean	SD	Mean	SD	
Scientific Concepts	3.6024	0.80624	3.7598	0.82439	-6.902***
Scientific Ability	4.3167	0.67962	4.5633	0.58938	-13.835***
Scientific Participation	4.2764	0.63634	4.4285	0.61207	-8.704***
Scientific Emotional Attitude	4.0294	0.56491	4.1272	0.56831	-6.171***
Scientific Spirit	4.1553	0.66489	4.3192	0.64176	-8.975***
Overall Mean	4.0340	0.50129	4.1969	0.48228	-11.838***

Through mean tests and independent samples t-tests on their gains, as shown in **Table 6**, the gains in scientific literacy for Year 4 and Year 5 pupils were 0.2207 and 0.2030 respectively, with Year 5 significantly higher than Year 4; Year 4 gains were significantly higher than Year 5.

Table 6. Analysis of value-added science literacy for students across grades.

Mean	Grade 4 (N = 6467)		Grade 5 (N = 6786)		t
	Mean	SD	Mean	SD	
Scientific Concepts	0.1951	0.31581	0.31581	0.33012	1.744
Scientific Ability	0.1191	0.31511	0.31511	0.31820	0.855
Scientific Participation	0.3838	0.89687	0.89687	0.88217	1.027
Scientific Emotional Attitude	0.2702	0.89678	0.89678	0.91257	1.265
Scientific Spirit	0.1351	0.42133	0.42133	0.42671	0.638
Overall Value-Added	0.2207	0.30426	0.30426	0.31047	2.057*

Table 7. Analysis of pre-test scientific literacy among students from different locations.

Mean	Urban (N = 7699)		Rural (N = 5553)		t
	Mean	SD	Mean	SD	
Scientific Concepts	3.9573	0.83749	3.3026	0.61687	30.683***
Scientific Ability	4.4957	0.59768	4.3699	0.70293	6.894***
Scientific Participation	4.3507	0.61531	4.3593	0.64664	-0.484
Scientific Emotional Attitude	4.1354	0.59162	4.0020	0.52566	8.337***
Scientific Spirit	4.2472	0.63820	4.2283	0.68499	1.011
Overall Mean	4.2099	0.49876	3.9892	0.46845	16.019***

Through mean tests and independent samples t-tests on the pre-test data for overall scientific literacy and its dimensions across urban and rural schools, as shown in **Table 7**, urban schools significantly outperformed rural schools in overall scientific literacy, scientific concepts, scientific abilities, and scientific attitudes and emotions. No significant differences were observed in scientific participation and scientific spirit and qualities.

Through mean tests and independent samples t-tests, as shown in **Table 8**, the value-added gains in scientific literacy for urban and rural schools were 0.1770 and 0.6394 respectively, indicating a significant difference. Across all dimensions except scientific participation, rural schools demonstrated significantly higher value-added gains than urban schools.

Table 8. Analysis of science literacy value-added by student location.

Mean	Urban (N = 7699)		Rural (N = 5553)		t
	Mean	SD	Mean	SD	
Scientific Concepts	0.2045	0.31258	0.1629	0.33616	4.488***
Scientific Ability	0.0793	0.32332	0.1649	0.30032	-9.623***
Scientific Participation	0.3812	0.89160	0.3605	0.88976	0.830
Scientific Emotional Attitude	0.1525	0.94174	0.2537	0.92922	-9.707***
Scientific Spirit	0.0954	0.43751	0.1810	0.39949	-7.267***
Overall Value-Added	0.1770	0.83784	0.6394	0.88914	-18.798***

Table 9. Analysis of pre-test scientific literacy levels among students in different districts and counties.

District/ County	Sci. Concepts Mean	Sci. Ability Mean	Sci. Participation Mean	Sci. Spirit Mean	Sci. Emotional Attitude Mean	Overall Mean
County A	3.6250	3.9341	4.0432	4.6968	3.8667	4.0331
County B	4.0201	3.8183	4.2089	3.5815	4.5201	4.0298
County C	4.0302	3.9131	4.2619	3.6304	4.5151	4.0701
County D	4.0402	3.6773	4.2020	3.5482	4.5302	3.9996
County E	4.6250	3.8030	4.0728	4.4056	3.9201	4.1653
County F	4.5352	3.9114	4.0477	4.2945	4.0101	4.1598
County G	4.0750	4.0364	4.2910	4.0393	4.3333	4.1550
County H	3.7500	4.0733	4.4575	4.1111	4.1667	4.1117
County I	4.1250	3.7865	4.2327	3.4890	4.5452	4.0357
County J	4.6250	3.7427	3.9823	4.3057	3.9101	4.1131
County K	3.9250	3.8384	4.1844	3.6438	4.5050	4.0193
County L	3.7500	4.0685	4.1321	4.1459	4.3333	4.0860

By comparing pre-test data, we examined the overall scientific literacy levels

across different counties. Among these, “County E”, “County H”, and “County J” demonstrated relatively strong overall scientific literacy, with scores of 4.1653, 4.1117, and 4.1131 respectively. Counties B, D, and K exhibited poorer overall scientific literacy, with scores of 4.0298, 3.9996, and 4.0193 respectively (**Table 9**).

Analysis of the value-added growth in scientific literacy across different countries, as shown in **Table 10**, reveals varying degrees of improvement. County C demonstrated the highest value-added growth at 0.3686, while County F exhibited the lowest at 0.0193.

Table 10. Analysis of value-added science literacy among students across different districts and counties.

District/County	Sci. Concepts VA	Sci. Ability VA	Sci. Participation VA	Sci. Spirit VA	Sci. Emotional Attitude VA	Overall Value-Added
County A	0.0200	0.0850	0.0467	0.0757	0.1750	0.0805
County B	0.2050	0.1767	0.9250	0.2214	0.2683	0.3593
County C	0.2850	0.2133	0.8900	0.2114	0.2433	0.3686
County D	0.2188	0.2117	0.9417	0.1743	0.2283	0.3549
County E	0.0200	0.0683	0.4067	0.2857	0.3317	0.2225
County F	0.0613	0.0133	0.0567	0.0100	-0.0450	0.0193
County G	0.2475	0.1550	0.5700	0.1243	0.1567	0.2507
County H	0.3075	0.0633	0.1133	0.0343	0.0533	0.1144
County I	0.2338	0.2233	1.0667	0.1686	0.2967	0.3978
County J	0.2163	0.1950	0.7100	0.1900	0.2417	0.3106
County K	0.2350	0.1983	0.8883	0.2057	0.2817	0.3618
County L	0.3213	0.0750	0.0783	0.0300	0.0767	0.1163

Table 11. Analysis of pre-test scientific literacy levels across schools.

School	Sci. Concepts Mean	Sci. Ability Mean	Sci. Participation Mean	Sci. Spirit Mean	Sci. Emotional Attitude Mean	Overall Mean
1	3.8789	3.5741	3.8114	3.6024	3.6816	3.7097
2	3.7965	4.0203	4.0386	4.3167	4.3669	4.1078
3	3.7645	3.7124	3.8453	4.2764	4.2752	3.9748
4	3.2300	3.8860	3.0393	3.9573	4.0566	3.6338
5	3.7974	3.5022	3.5076	4.4957	4.3167	3.9239
6	4.2174	4.0130	3.1265	4.3507	4.2764	3.9968
7	4.0658	3.7664	3.9206	4.1354	4.0294	3.9835
8	4.1255	4.7619	3.8366	4.2472	3.7124	4.1367
9	3.6486	3.9464	3.5842	3.7124	4.2860	3.8355
10	3.1060	4.0147	4.2358	4.8860	3.5022	3.9489

Ten schools were randomly selected from the surveyed institutions to compare differences in student scientific literacy gains. Analysis of pre-test data revealed varying levels of scientific literacy across schools. School 2 and School 8 demonstrated relatively strong overall scientific literacy at 4.1078 and 4.1367 respectively, while School 4 and School 1 showed slightly weaker performance at 3.6338 and 3.7097 (**Table 11**).

Analysis of the value-added gains in scientific literacy across different schools, reveals varying outcomes. School 5 demonstrated the highest gain at 0.4676, while School 7 recorded the lowest at 0.1976, gains in scientific concepts ranged from 0.1156 to 0.4288, gains in scientific abilities from 0.1275 to 0.3750, gains in scientific participation from 0.1250 to 0.6400, gains in scientific attitudes from 0.1050 to 0.5425, and gains in scientific spirit and qualities from 0.2200 to 0.5625 (**Table 12**).

Table 12. Analysis of science literacy value-added among students from different schools.

School	Sci. Concepts VA	Sci. Ability VA	Sci. Participation VA	Sci. Attitude VA	Sci. Spirit VA	Overall Value-Added
1	0.3289	0.2325	0.6400	0.2725	0.5625	0.4073
2	0.3200	0.2150	0.3850	0.5300	0.4850	0.3870
3	0.3467	0.1275	0.3700	0.5425	0.5150	0.3803
4	0.3133	0.3200	0.2800	0.4250	0.4625	0.3607
5	0.3356	0.3750	0.5800	0.5225	0.5250	0.4676
6	0.2556	0.2900	0.2550	0.2100	0.2200	0.2461
7	0.1156	0.3700	0.1250	0.1050	0.2725	0.1976
8	0.2756	0.3425	0.2600	0.2500	0.4975	0.3251
9	0.3978	0.2450	0.5000	0.2300	0.2750	0.3296
10	0.4822	0.4250	0.5200	0.2125	0.5325	0.4344

4. Causes of Challenges in Enhancing Primary Pupils' Scientific Literacy

Drawing upon prior literature and survey data, this paper employs the CIPP model to analyze the current challenges and underlying causes hindering the enhancement of primary pupils' scientific literacy.

4.1. Contextual Level: Policy and Educational Ecosystem Discrepancies

At the contextual level, policy and educational ecosystem discrepancies significantly impact primary science education. A notable gap exists between policy formulation and implementation; while the Compulsory Education Science Curriculum Standards (2022 Edition) designate scientific literacy as a core objective, its effective classroom implementation remains challenging, reflecting the marginal-

ized status of science education within the current basic education system. Primary science textbooks are relatively simplistic, and a widespread reduction in teaching hours is prevalent, with 35.9% of classes experiencing insufficient teaching time (Lei et al., 2021). This imbalance in allocated hours leads to skewed resource distribution within schools, creating a predicament where policy, evaluation, and practice are misaligned. Furthermore, the implementation of science education in primary and secondary schools has yet to establish a collaborative co-education mechanism involving families, schools, and society (Zhou & Xiang, 2023). Parents generally equate science education with the dissemination of scientific knowledge, confining it to school and classroom settings (Zhang, 2023), thereby exacerbating practical obstacles to science curriculum implementation. Resource allocation between urban and rural areas exhibits a Matthew effect, with urban students scoring significantly higher (4.2099) than rural students (3.9892) in pre-test science literacy, directly undermining educational equity (Figure 1).

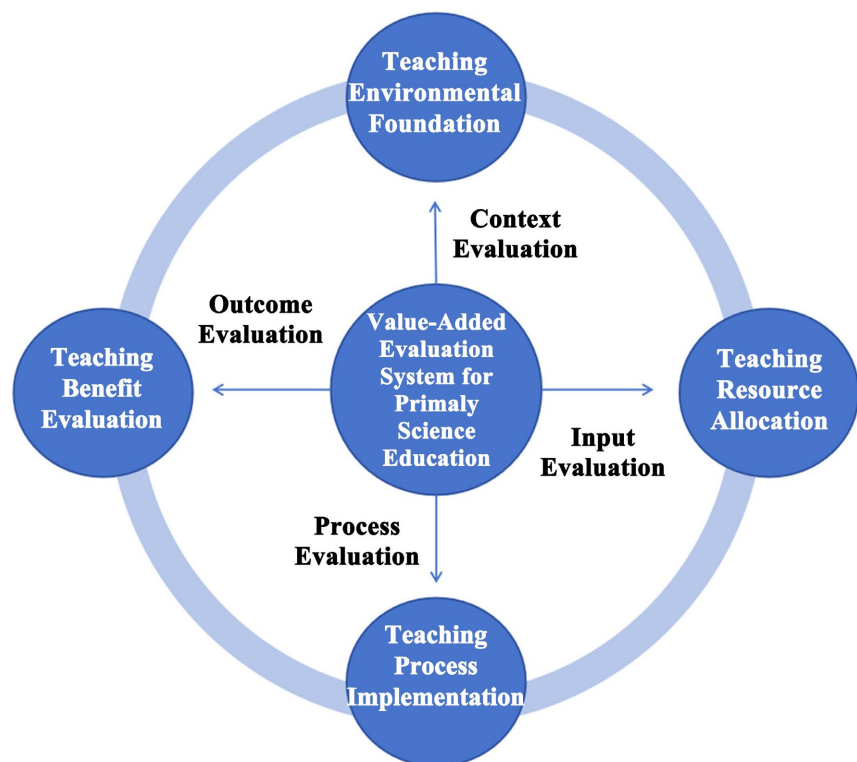


Figure 1. Model of value-added evaluation system for primary science education.

4.2. Input Level: Weak Supporting Conditions

Moving to the input level, weak supporting conditions hinder the effective delivery of science education. A notable phenomenon is the underutilization of experimental equipment despite adequate procurement, with 63% of schools using demonstration equipment fewer than five times annually. This reflects a severe disconnect between resource allocation and actual teaching needs, resulting in a sharp reduction in hands-on practical opportunities for pupils, as evidenced by

their lowest mean pre-test science competency score of 3.8998. Additionally, the integration of information technology and science education remains superficial; while smart classrooms are relatively well-equipped, the routine application of technologies such as VR in science teaching is still in its infancy, proving ineffective in enhancing pupils' scientific literacy. Systemic deficiencies also exist in primary science teachers' development, with over 70% lacking STEM backgrounds (Zheng et al., 2023), directly undermining pupils' scientific literacy. The specialized curriculum system for science education requires optimization, as current teacher training programmes lack integrated courses and skills-based modules, with insufficient emphasis on experimental and practical teaching. Concurrently, teaching resources and assessment methods remain limited in variety (Zhao, 2019).

4.3. Process Level: Implementation Issues in Teaching and Assessment

At the process level, implementation issues in teaching and assessment further compound challenges. A pronounced tendency towards formulaic instructional practices exists, with teacher-dominated behaviour accounting for an average of 81.3% of classroom time during inquiry activities, leaving pupils with a median of merely 7.4 minutes per lesson for genuine independent inquiry (Pei & Liu, 2018). Regional imbalances in curriculum development capabilities are also evident, with significant disparities in the value-added gains of pupils' scientific literacy (a range of 0.35) and primary schools in remote mountainous areas lacking practical materials and equipment, resulting in insufficient curriculum development capabilities (Wang, 2018). Traditional assessment methods are outdated, struggling to support detailed analysis and measurement of classroom data in real-world contexts (Zou & Zhang, 2025), further contributing to suboptimal teaching effectiveness in science instruction. Moreover, the disconnect between form and substance in formative assessment is prevalent, with some primary teachers merely adhering to the literal meaning of formative assessment, resulting in evaluations confined to the learning process without substantially enhancing pupils' scientific literacy (Ge, 2022).

4.4. Outcomes Level: Disconnect in Educational Output Transformation

Finally, at the outcomes level, a disconnect in educational output transformation undermines the cultivation of core competencies (Li, 2024). Insufficient attainment of scientific practical abilities is evident, as teachers predominantly employ lecture-based instruction in science courses (Wan, 2024), hindering the development of students' practical competencies, with pupils' pre-test science ability mean being the lowest at merely 3.8998. The absence of a systematic design for science curriculum progression disrupts the organic transition from primary science to subject-specific secondary courses, thereby undermining learning continuity. Furthermore, the dissemination effectiveness of high-quality resources is low, with a

significant volume of outstanding educational research achievements lacking mechanisms for promotion and application (Wu & Song, 2022), exacerbating regional disparities in scientific literacy among primary and secondary school students. The development of collaborative social networks remains underdeveloped, with overall utilization of science and technology venues among primary and secondary school pupils being insufficient, with only 7.2% having visited four or more times (Xie et al., 2018), and school-community partnerships often remaining confined to the level of agreements, failing to establish evaluation mechanisms bridging the class to society.

5. Conclusions and Recommendations

5.1. Research Findings

The research findings reveal an uneven developmental pattern across different dimensions of students' scientific literacy. Although the mean value-added gain in overall scientific literacy was 0.2116, indicating a positive upward trend, significant structural imbalances were observed. Specifically, scientific participation showed the highest gain (0.3707), while scientific competence not only had the lowest pre-test score (3.8998) but also the smallest improvement (0.1152). In addition, scientific attitudes and emotions recorded the highest pre-test mean (4.7180), yet their value-added increase remained moderate at 0.2538.

The study also identified significant group differences in science literacy value-added outcomes. Although no notable gender-based disparity in gains was found, female students demonstrated higher pre-test performance and greater engagement. In urban-rural comparisons, urban schools led in pre-test scores, whereas rural schools showed stronger gains, suggesting considerable catch-up potential. Furthermore, while Year 5 pupils outperformed Year 4 in pre-test measures, Year 4 pupils achieved significantly higher value-added gains, highlighting the need to sustain developmental momentum into upper grades. Substantial variations were also evident across districts and individual schools: County C and School 5 exhibited outstanding value-added performance, in contrast to County F and School 7, which demonstrated weaker growth—pointing to persistent regional and inter-school imbalances.

To further contextualize student-level scientific literacy outcomes (pre-test performance and value-added gains), teacher and parent questionnaire data were systematically linked to student results via three core mechanisms. First, teachers' data on school science education conditions explained students' weak performance in specific dimensions: the pre-test showed the lowest mean score (3.8998) in "scientific ability", and 63% of schools reported using demonstration equipment fewer than five times yearly, confirming insufficient hands-on practice (due to low equipment use) directly caused this weakness. Second, parents' data on family science education support validated drivers of student group differences. Finally, cross-stakeholder data (teacher and parent feedback) revealed systemic mismatches in science education resources; the "resource utilization gap" (available

equipment not integrated into daily teaching) directly explained why “scientific ability”—most dependent on practice—had the smallest value-added gain (0.1152).

Consequently, value-added assessment has proven effective in revealing the “net effect” of science education. It adopts a comprehensive process encompassing pre-tests, process tracking, and post-tests to enable dynamic evaluation of science education outcomes, with gain scores serving as a critical and valid indicator for measuring value added. The validity of gain scores lies in two aspects: they quantify students’ progress in scientific literacy dimensions intuitively by directly comparing pre-test and post-test data, avoiding the one-sidedness of judging only by absolute levels; meanwhile, they require no complex statistical assumptions or model fitting and can be calculated via basic tools, ensuring both operational convenience and result objectivity to provide reliable data for subsequent analysis. This evaluation model, combining a “comprehensive process with gain scores”, not only offers a clearer view of educational progress but also provides data-driven support for the targeted allocation of educational resources.

5.2. Recommendations for Improvement

To drive meaningful improvement in primary science education, it is essential to first optimize the policy ecosystem and reinforce the strategic position of science education. This requires providing robust support for top-level design and ensuring equitable resource allocation to foster scientific literacy. Science education should be incorporated as a core component of local education supervision and evaluation systems. Mechanisms must be established to balance resource distribution between urban and rural areas, ensuring that appropriate basic experimental equipment and safety facilities are allocated. Additionally, fostering inter-school resource-sharing platforms can help maximize the impact of available resources and promote collaborative learning.

Strengthening the support system is equally crucial to enhance the quality of science education implementation, as science teachers play a pivotal role in cultivating pupils’ scientific literacy. Expanding enrollment in science education programs at teacher training institutions and encouraging graduates with STEM backgrounds to pursue primary science teaching can help address teacher shortages and improve expertise. Prioritizing the development of practical skills, such as inquiry-based lesson design, will further empower teachers. Concurrently, establishing platforms to monitor teaching equipment utilization efficiency can optimize resource use. Developing VR/AR-assisted teaching modules tailored for primary pupils and constructing regionally distinctive experimental case repositories will enrich the learning experience and make science education more engaging and relevant.

Deepening teaching reform is vital to foster competency-oriented classroom ecosystems, as teaching methodologies directly influence pupils’ scientific literacy development. The “learning by doing” approach should be comprehensively promoted, with experiments designed to align with pupils’ developmental stages and

interests. Developing cross-curricular thematic learning units can help pupils see the connections between science and other subjects, fostering a more integrated understanding. Establishing science curriculum continuity between primary and secondary levels and dynamically adjusting knowledge progression will ensure a seamless transition and sustained interest in science.

Innovating the evaluation system is also necessary to leverage the guiding role of value-added assessment in facilitating sustained enhancement of pupils' scientific literacy. Constructing a "foundational and value-added" evaluation model that incorporates growth metrics into performance reviews and commendations can provide a more holistic view of pupil progress. Strengthening the assessment of experimental processes and developing digital tools to track scientific thinking development trajectories will offer deeper insights into pupil learning. Collaboratively building inter-school lesson examples and home-school-community science outreach practices can foster a multi-stakeholder collaborative educational ecosystem, ensuring that science education is supported and enhanced at all levels.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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