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Effectiveness of formative assessment strategies on learning outcomes in science education

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Abstract
Formative assessment is widely promoted as a way to improve learning in science classrooms, yet the strength of the evidence is less settled than its popularity suggests. This narrative review synthesizes recent meta-analyses, an umbrella review, and science-specific empirical studies, mostly from 2023 to 2026, to examine how feedback, student self- and peer assessment, technology-supported tools and adaptive teaching relate to learning outcomes in K–12 science education. Pooled estimates are positive but modest: a 2024 meta-analysis of 118 studies reported an average Hedges' g of 0.25, and an umbrella review found no harmful effects but rated the certainty of the evidence low to very low. Science-specific effects appear smaller than headline figures, and a 2023 thesis suggests that weaker study designs inflate estimates. Implementation is a persistent problem, an observational study of 45 primary science teachers in Jordan found formative practices at a low level on every criterion. The paper argues that sustained teacher professional development, student-directed approaches suited to students' age, and stronger experimental evidence in science are the main priorities. Subject area: education, assessment, context: K–12 science education.

Keywords: Formative assessment, science education, feedback, meta-analysis, teacher professional development, K–12

Introduction

Formative assessment refers to the ongoing collection and use of evidence about learning so that teachers and students can adjust what they do next. Policymakers in many systems treat it as a core element of teaching, and an umbrella review of meta-analyses notes that teacher training and sustained professional support are central to whether it works in practice (Sortwell *et al*., 2024) [4]. In science, it carries extra appeal: misconceptions are common, inquiry tasks generate rich evidence of reasoning, and curricula ask students to explain, not only recall.

Early claims of large gains have been tempered. This paper asks three questions. Which formative assessment approaches are most discussed in recent science-relevant literature? What does the evidence say about their effect on learning outcomes? What stands in the way of effective implementation? The focus is K–12 science education, with attention to evidence drawn from general K–12 reviews where science-specific syntheses are thin.

Review Approach

This is a narrative review, not a registered systematic review. In November 2026, I searched the open web and publisher sites using combinations of formative assessment, assessment for learning, feedback, science education, meta-analysis, systematic review and teacher practice. I prioritized peer-reviewed meta-analyses and reviews published from 2023 onward, then added recent empirical studies in science classrooms. One Master's thesis is included because it directly examines publication bias and design quality, and is labeled as such. I read two sources in full (Sortwell *et al*., 2024; AlAli & Al-Barakat, 2025) [1, 4] and relied on abstracts for the others, so findings from earlier meta-analyses are reported only as summarized in the sources I accessed. Studies in other languages or in databases I could not reach may have been missed.

Formative Assessment Approaches in Science Education

Teacher feedback and questioning

Feedback and classroom questioning are the most familiar forms of formative assessment. In science they are used to surface prior conceptions and probe reasoning during practical work. Evidence on feedback is mixed. A study of 9,841 fifteen-year-olds from Mainland China using PISA 2015 data found that students' perceptions of teachers' adaptive instruction were positively linked with science achievement, whereas perceived teacher feedback showed a near-zero association with achievement and a direct negative effect that was offset by positive indirect effects through science interest (Zhang *et al*., 2025) [6]. This was correlational, but it suggests that feedback is not automatically helpful and may depend on how it shapes motivation.

Student-directed assessment: self-assessment, peer assessment and rubrics

Student-directed strategies aim to build self-regulation. In the umbrella review, one included meta-analysis found larger effects for student-directed than teacher-directed formative assessment across subjects, though the effect depended on age: rubrics, for example, helped more as students got older and showed a slightly negative effect on self-regulated learning among primary students (Sortwell *et al*., 2024 [4], summarizing Panadero *et al*., 2023). The practical implication is that a technique effective in secondary classrooms cannot be assumed to work with younger children.

Technology-supported and gamified assessment

Digital tools can speed up feedback. The umbrella review reported a large effect for student response systems and a small effect for gamified assessment tools, while cautioning that novelty may account for some short-term gains (Sortwell *et al*., 2024) [4]. A 2025 meta-analysis of 42

studies on AI-enabled "intelligent feedback" in inquiry-based science learning reported moderate positive effects on achievement and perceptions, with effectiveness shaped by feedback timing, technique and learner control over feedback (Zheng *et al*., 2025).

Adaptive teaching and instructional adjustment

Collecting evidence matters only if teaching changes in response. The umbrella review summarized one meta-regression in which planned instructional adjustment had a small moderating effect, while unplanned adjustment had a trivial one (Sortwell *et al*., 2024 [4], summarizing Lee *et al*., 2020). This is consistent with the PISA finding on adaptive instruction (Zhang *et al*., 2025) [6].

Evidence on Effectiveness

Pooled estimates favor formative assessment but are modest. A 2024 meta-analysis of 118 studies and 258 effect sizes reported an overall Hedges' g of 0.25, and found similar effects across types of formative assessment and content areas, including science (Yao *et al*., 2024) [5]. Effects were larger for high school students, for studies outside North America and Western Europe, and for quasi-experimental designs. An umbrella review of 13 meta-analyses likewise found no negative effects, with magnitudes ranging from trivial to large depending on the strategy (Sortwell *et al*., 2024) [4].

Two caveats matter for science. First, science-specific estimates were small: the umbrella review reported trivial effects (standardized mean differences of about 0.09 to 0.13) in two meta-analyses covering science, compared with a small effect for mathematics (Sortwell *et al*., 2024) [4]. Second, design quality may inflate results. A 2023 Oxford Master's thesis found a pooled g of 0.31 across 38 studies, which fell to 0.16 after adjustment for publication bias, and argued that earlier estimates were inflated by weaker designs, although fewer than 10% of interventions were detrimental (Dudley, 2023) [3]. The umbrella review reached a similar conclusion about certainty: methodological quality of the included meta-analyses was mostly moderate, but robustness was very low for nine, low for three and moderate for one (Sortwell *et al*., 2024) [4]. Taken together, the evidence supports using formative assessment while discouraging confident claims about how much it will raise science achievement.

Barriers and Challenges to Implementation

The most consistent barrier is teacher capacity. In an observational study of 45 primary science teachers in northern Jordan, practice was rated low on every criterion, including planning learning objectives, gathering evidence, giving feedback, organizing self- and peer assessment, and revising instruction using evidence; gender and years of experience made no significant difference, which the authors read as evidence that experience alone does not build these skills (AlAli & Al-Barakat, 2025) [1]. The umbrella review similarly highlights the need for substantial time and ongoing professional support (Sortwell *et al*., 2024) [4], and it summarized one meta-regression in which ongoing professional development had the greatest effect while teachers with none showed no significant effect.

Other barriers are structural and methodological. Most meta-analyses mix primary, secondary and tertiary students, which limits what can be said about school science specifically, and few examine moderators such as gender or school socioeconomic context (Sortwell *et al*., 2024) [4]. A 2026 systematic review addressing formative assessment for multilingual learners in U.S. K–12 STEM classrooms reflects growing attention to equity as a design concern (Ayik *et al*., 2026) [2]. I did not find recent science-specific reviews of resource constraints such as class size or laboratory time, so I do not draw conclusions on them here.

Discussion and Implications

The evidence supports a measured stance. Formative assessment is unlikely to harm and often helps, but gains in science are probably smaller than early enthusiasm implied, and they depend on implementation. Three implications follow. First, professional development should be ongoing and practice-based, aimed at the specific weaknesses documented in science classrooms: setting clear success criteria, gathering evidence through activities, and acting on it. Second, strategies should be matched to students' age and subject demands; rubrics and self-regulation scaffolds may suit secondary students better than primary pupils. Third, technology should support, not replace, teacher judgment, with attention to timing and learner control of feedback.

For research, priorities include randomized or well-controlled studies within science, separate reporting for primary and secondary students, and outcomes beyond tests, such as scientific reasoning and interest. The limits of this review are real: it is narrative, relies partly on summaries of studies, and includes one unpublished thesis and several cross-sectional or observational studies that cannot establish causation.

Conclusion

Recent syntheses indicate that formative assessment yields positive but modest benefits for learning, with science-specific evidence thin and of uncertain quality. Feedback, student-directed assessment, digital tools and adaptive teaching each show promise, yet their effects depend on student age, design quality and, above all, teachers' capacity to use evidence. Investing in sustained teacher development and better-controlled science studies is likely to do more for learning than adding new tools alone.

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