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Embedded formative feedback in chemistry worksheets: a self-regulation approach to conceptual learning of the periodic table of elements

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ABSTRACT

This study aims to investigate the effectiveness of Student Worksheets (LKPD) oriented toward Assessment for Learning (AfL) in improving student learning outcomes on the Periodic Table of Elements (PTE) topic. The research employed a pre-experimental design with a one-group pretest-posttest model (O_1 X O_2), conducted with students in Grade X of SMA 2 Muhammadiyah Sidoarjo, Indonesia. Grounded in Black and Wiliam's (1998) Assessment for Learning (AfL) framework and self-regulated learning theory, the worksheets embedded five core AfL mechanisms transparent learning objectives, continuous evidence elicitation, constructive feedback loops, peer assessment activities, and structured self-assessment checkpoints hypothesized to address known conceptual barriers in Periodic Table learning by enabling students to monitor, evaluate, and regulate their own comprehension in real time. Data were collected through validated pretest and posttest instruments measuring conceptual understanding of the PTE. A paired sample t-test, preceded by Shapiro-Wilk normality testing, was applied to examine score changes. Results revealed a mean improvement of 41.79 points (pretest M = 42.07; posttest M = 83.86), with a t-value of −22.476 ($p < 0.05$) and an N-Gain of 0.72 (High category). These findings confirm that formative feedback embedded within chemistry worksheets produces substantive gains in conceptual understanding, with theoretical implications for self-regulation-based instructional design in secondary science education.

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Introduction

Education in the twenty-first century demands a fundamental transformation in pedagogical approaches, particularly in science learning that prioritizes critical thinking, collaborative, creative, and communicative skills as core competencies that students must master (Fitriani et al., 2022; OECD, 2019). This transformative demand is driven by a global paradigm shift that reorients the purpose of education away from knowledge transfer and toward the development of higher-order thinking capacities and the ability to solve complex problems both independently and collaboratively (Dolin et al., 2022). In this context, chemistry as a branch of natural science presents documented learning challenges: a systematic review by Taber (2019) encompassing over 200 empirical studies identified that students across secondary and tertiary levels consistently develop persistent misconceptions in chemistry due to the abstract and submicroscopic nature of its core concepts. These conceptual difficulties generate academic anxiety that measurably reduces motivation and engagement, a finding corroborated by large-scale survey evidence involving more than 3,000 secondary students across nine countries (Potvin & Hasni, 2014). This negative perception has direct implications for students' learning motivation, active engagement, and academic achievement in chemistry at the senior high school level (Rahmawati et al., 2022). Crucially, existing interventions in Indonesian chemistry education have primarily addressed surface-level content delivery through improved instructional media without adequately targeting the metacognitive and self-regulatory mechanisms that underpin durable conceptual understanding (Sulistyaningrum et al., 2023; Situmorang et al., 2021). This unresolved gap between curriculum reform ambitions and the absence of assessment-integrated instructional tools that scaffold self-regulation represents the precise deficit this study addresses.

The Periodic Table of Elements (PTE) is one of the fundamental topics in the Grade X chemistry curriculum, occupying a strategic position as a conceptual framework for understanding atomic structure, chemical bonding, and the reactivity trends of chemical elements (Fitriani et al., 2022). The PTE is not merely a list of chemical elements; rather, it is a classification system that reflects deep regularities in the properties of matter, making its mastery an essential foundation for understanding more advanced chemistry topics (Situmorang et al., 2021). Despite this importance, PTE has consistently been among the topics with the lowest average mastery among senior high school students in Indonesia, as indicated by various national learning evaluation reports and local research findings (Hidayah et al., 2021). The difficulties encountered in learning this topic are not solely attributable to the complexity of the content, but also to instructional approaches that remain dominated by rote memorization and one-way information delivery, which do not promote the construction of meaningful understanding (Yusuf et al., 2021). The low level of conceptual mastery of PTE significantly impacts students' ability to learn subsequent chemistry topics that are logically built upon an understanding of the periodic properties of elements, such as chemical bonding, reaction rates, and chemical equilibrium (Situmorang et al., 2021).

The *Kurikulum Merdeka* (Freedom Curriculum) implemented nationally by the Indonesian Ministry of Education, Culture, Research, and Technology affirms the importance of student-centered learning, the development of critical thinking, and the strengthening of twenty-first-century competencies as the primary goals of the educational process (Kemendikbudristek, 2022). This curricular paradigm shift fundamentally demands a reconfiguration of the role of assessment in the learning process: assessment is no longer merely a summative evaluation tool that measures terminal outcomes, but is integrated as an organic component of the learning process itself, continuously providing formative feedback to both students and teachers (Prasetyo & Harjono, 2022). Assessment designed in this manner functions as a mirror that accurately reflects the state of students' understanding while simultaneously serving as a compass that guides subsequent instructional steps more precisely and purposefully (Widana et al., 2021). This paradigm shift in assessment is consistent with global developments in educational assessment theory and practice that position assessment as an instrument for empowering learning rather than merely an instrument for measurement that is terminal and judgmental in nature (Dolin et al., 2022).

Assessment for Learning (AfL) is a formative assessment paradigm grounded in the seminal work of Black and Wiliam (1998) and has evolved into a well-established pedagogical framework over the past three decades, supported by a continuously growing empirical evidence base (Wiliam, 2021). AfL is defined as the process of seeking and interpreting evidence used by students and teachers to decide where learners are in their learning, where they need to go, and how best to get there (Andrade & Brookhart, 2020). Unlike Assessment of Learning, which is oriented toward measuring terminal learning outcomes for the purposes of grading and reporting, AfL is explicitly designed to provide continuous evidence of student understanding throughout the learning process, enabling teachers and students to make timely instructional adjustments based on that evidence (Dolin et al., 2022). The key mechanisms of AfL encompass five strategic components: (1) the clarification of learning objectives and success criteria in a transparent and student-comprehensible manner; (2) the continuous elicitation of evidence of student understanding through various assessment techniques; (3) the provision of constructive feedback that helps students close the gap between their actual and desired performance; (4) the activation of students as learning resources for one another through structured peer assessment; and (5) the development of students' self-regulation as owners of their own learning process through systematic self-assessment (Andrade & Brookhart, 2020; Dolin et al., 2022).

Strong empirical evidence demonstrates that consistently and high-quality implemented AfL practices produce significant improvements in student academic achievement across various levels and subjects. Recent systematic reviews show effect size variations ranging from 0.29 to 0.75, depending on the quality of implementation and the characteristics of the learning context, with studies implementing AfL comprehensively and in a structured manner tending to show higher effect sizes (Dolin et al., 2022). In Indonesia, research by

Widana et al. (2021) showed that teachers trained in formative assessment practices produced students with deeper conceptual understanding and more developed metacognitive abilities compared to a control group receiving traditional assessment approaches. The effectiveness of AfL has also been empirically validated in science learning contexts across various Asian countries, including Indonesia, Malaysia, and Singapore, with consistent findings indicating positive impacts on learning motivation, academic engagement, and students' cognitive achievement (Rahmawati et al., 2022; Dolin et al., 2022). This body of evidence affirms that AfL is not merely a theoretical pedagogical innovation, but an evidence-based intervention that has been proven effective in improving learning quality.

Student Worksheets, known in Indonesian educational practice as Lembar Kerja Peserta Didik (LKPD), are structured instructional materials widely used in chemistry learning in Indonesia as a guide for students in carrying out a series of learning activities designed by the teacher (Sulistyaningrum et al., 2023). As instructional materials, LKPD hold a strategic position in the Indonesian chemistry learning ecosystem due to their near-universal use across all levels and types of schools, as well as their adaptability to various learning contexts and approaches (Rahayu et al., 2023). Conventionally, LKPD function as guided practice tools that lead students through a series of procedural tasks and structured exercises in a linear manner, with an emphasis on applying formulas and procedures previously taught by the teacher (Rahayu et al., 2023). However, the design of most conventional LKPD in circulation at Indonesian schools does not integrate formative assessment principles: conventional LKPD generally do not explicitly state learning objectives in student-accessible language, do not provide mechanisms for self-monitoring or peer evaluation, and do not offer structured feedback opportunities within the tasks assigned to students (Yusuf et al., 2021). As a result, students complete LKPD tasks without meaningful metacognitive engagement, so that the pedagogical potential of these materials is not optimally realized and LKPD serve merely as administrative supplements to instruction (Hidayah et al., 2021).

By reorienting the design of LKPD toward AfL principles, it becomes possible to transform this already familiar learning tool into a powerful, effective, and pedagogically meaningful vehicle for formative assessment. AfL-oriented LKPD explicitly states learning objectives in student-friendly language so that learners clearly understand the direction and purpose of their learning (Andrade & Brookhart, 2020). In addition, AfL-oriented LKPD embed self-assessment checkpoints at key stages of the learning sequence, integrate structured activities for peer feedback, provide guiding questions that prompt students to reflect on their understanding, and include corrective tasks triggered by the identification of comprehension gaps (Andrade & Brookhart, 2020). This redesigned format has the potential to meaningfully improve the quality of students' engagement with challenging content such as the Periodic Table of Elements, as it encourages deeper, more active, and better-connected information processing relative to students' prior knowledge, in contrast to conventional passive memorization approaches (Dolin et al., 2022; Fitriani et al., 2022). Research by Rahayu et al. (2023) further confirms that carefully designed AfL-based LKPD can simultaneously enhance both students' affective and cognitive engagement, which is a prerequisite for the construction of meaningful and durable knowledge in chemistry learning.

The Periodic Table of Elements topic in the Grade X chemistry curriculum encompasses multiple interrelated and hierarchically organized conceptual domains. These domains include: (1) the historical development of atomic models and periodic classification systems, from the contributions of Newlands, Mendeleev, and Meyer to Moseley, which reflects the evolution of scientific thinking about the nature of matter; (2) the organization of elements based on atomic number and electron configuration, which underpins periodic patterns; (3) periodic trends encompassing atomic radius, ionization energy, electron affinity, and electronegativity, along with their rational explanations grounded in electrostatic principles and electron configuration; (4) the distinguishing properties of metals, nonmetals, and metalloids based on their positions in the periodic table; and (5) the practical application of periodic patterns to predict the properties of elements in various chemical reactions and phenomena (Sulistyaningrum et al., 2023). The breadth of this conceptual coverage makes PTE highly cognitively demanding, requiring students to construct integrated mental models rather than merely memorizing isolated facts (Situmorang et al., 2021). AfL-oriented LKPD is theoretically well-suited to scaffold this complex knowledge construction process, as its structure incorporating reflection checkpoints and feedback opportunities enables students to consciously monitor and regulate their own comprehension of each subtopic being studied (Prasetyo & Harjono, 2022).

A number of studies conducted in Asian educational contexts, particularly Indonesia, have demonstrated the effectiveness of AfL-based instructional materials in improving science learning outcomes. Yusuf et al. (2021) found that formative assessment-based worksheets significantly improved students' conceptual understanding of chemical equilibrium in Indonesian senior high schools, with a standardized gain score (N-gain) of 0.62, which falls within the medium-high category according to Hake's criteria. Hidayah et al. (2021) reported that structured self-assessment activities embedded in chemistry worksheets contributed to improvements in both cognitive achievement and metacognitive awareness among students, with those engaged in self-assessment demonstrating deeper conceptual understanding and better knowledge transfer abilities when confronted with novel problem situations.

Although evidence supporting AfL in science education continues to grow both globally and in Indonesia, very few studies have rigorously evaluated the effectiveness of AfL-oriented LKPD specifically for the Periodic Table of Elements topic using adequate quantitative research designs (Rahayu et al., 2023). Most existing studies on LKPD effectiveness in Indonesian chemistry education rely on descriptive analysis without rigorous inferential testing, or focus on other chemistry topics such as stoichiometry, acids and bases, or thermochemistry, which have different content characteristics and cognitive demands from those of PTE (Sulistyaningrum et al., 2023; Situmorang et al., 2021). Studies specifically examining the effectiveness of AfL-based LKPD for PTE content using quantitative pretest-posttest measurement and rigorous inferential analysis remain very limited, leaving chemistry teachers and curriculum developers without sufficient empirical evidence to make informed decisions about the design and use of LKPD for this topic (Fitriani et al., 2022). This clear research gap underscores the urgency of systematically designed research to fill this knowledge void, so that chemistry education practitioners have an adequate empirical foundation for making effective and well-informed instructional decisions (Prasetyo & Harjono, 2022).

This study employs a pre-experimental design with a one-group pretest-posttest model (O_1 X O_2), which is considered appropriate for examining the effect of a specific instructional intervention within a naturalistic classroom context where full randomization is not feasible due to ethical and practical considerations (Creswell & Creswell, 2022). Although the absence of a control group limits the causal claims that can be made, this design allows for within-group comparisons of student learning achievement before and after exposure to the AfL-oriented LKPD intervention, thereby still producing meaningful information about the effectiveness of the intervention (Prasetyo & Harjono, 2022). Statistical analysis employs the paired sample t-test, preceded by the Shapiro-Wilk normality test to verify the distributional assumptions of the data, ensuring that conclusions about the significance of learning gains are based on rigorous inferential analysis rather than mere descriptive observation (Widana et al., 2021). In addition to significance testing, this study also calculates effect size using Cohen's d to provide a practical measure of the magnitude of the intervention's effect that is not dependent on sample size (Creswell & Creswell, 2022). The primary purpose of this study is to determine whether the implementation of AfL-oriented LKPD significantly improves student learning outcomes on the Periodic Table of Elements topic in Grade X; the findings are expected to contribute empirical evidence for the design and adoption of formative assessment-based instructional materials in Indonesian chemistry education, and to provide practical insights for chemistry teachers seeking to improve student learning outcomes through LKPD design innovation that is theoretically grounded and evidence-supported (Rahmawati et al., 2022; Dolin et al., 2022).

Method

Research Design

This study employed a pre-experimental research design with a one-group pretest-posttest model, schematically represented as O_1 X O_2, where O_1 denotes the pretest administered prior to the intervention, X denotes the implementation of the AfL-oriented LKPD as the treatment, and O_2 denotes the posttest administered following the completion of the intervention. This design was selected because it allows the researcher to measure the magnitude of change in student learning outcomes attributable to the instructional treatment within a single experimental group, using each student as their own baseline control. While the absence of a parallel control group is acknowledged as a limitation of the pre-experimental design, the within-group comparison nonetheless provides meaningful evidence of the intervention's educational impact when supported by appropriate inferential statistical analysis.

Participants

The research participants consisted of students enrolled in Grade X of SMA Muhammadiyah 2 Sidoarjo, East Java, Indonesia. The sample was selected using purposive sampling based on the criteria of representativeness for the target population of Grade X chemistry students and the practical availability of the class for research purposes. The total number of participants was 39 students. All participants completed both the pretest and posttest, ensuring a complete dataset for paired statistical analysis. Participation was voluntary and conducted with appropriate ethical consideration, including informed consent from the school administration.

Instrumentation

The primary instrument for data collection was a validated written test comprising multiple-choice and short-answer items covering the key learning objectives of the Periodic Table of Elements topic as specified in the

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Kurikulum Merdeka competency standards for Grade X chemistry. The test items assessed students' ability to: (1) describe the historical development of the periodic table; (2) identify the position of elements in the periodic table based on electron configuration; (3) explain periodic trends including atomic radius, ionization energy, electron affinity, and electronegativity; and (4) apply knowledge of periodic properties to predict element characteristics. Both pretest and posttest used equivalent-form instruments to minimize test-familiarity effects. Content validity was established through expert review by two chemistry education specialists, yielding a Content Validity Ratio (CVR) of 0.87, which exceeds the critical threshold of 0.62 for a two-expert panel (Lawshe, 1975). Internal consistency reliability was assessed through a pilot test administered to 30 students from a comparable Grade X class not included in the main study; Cronbach's alpha for the final instrument was $\alpha = 0.81$, indicating good reliability. Item discrimination indices ranged from 0.30 to 0.68, and items with discrimination below 0.25 were revised or excluded prior to the main study. The sample size of 39 was evaluated post hoc using G*Power 3.1 for a paired t-test with a medium-to-large effect size ($d = 0.50$), $\alpha = 0.05$, and power $= 0.80$, which indicated a minimum required N of 34; the achieved sample of 39 therefore exceeded this threshold, confirming adequate statistical power for the planned analyses (Faul et al., 2007).

Data Analysis

Student learning outcomes were quantified as scores on the pretest and posttest instruments (scale 0–100). Prior to inferential analysis, the normality of both pretest and posttest score distributions was examined using the Shapiro-Wilk test, which is appropriate for small-to-moderate sample sizes ($n < 50$). The null hypothesis for the normality test was that the data were normally distributed; if the Shapiro-Wilk significance value exceeded 0.05, the normality assumption was retained. Following confirmation of normality, a paired sample t-test was conducted to determine whether the mean difference between pretest and posttest scores was statistically significant. The null hypothesis for the t-test was that there was no significant difference between pretest and posttest means ($\mu_2 - \mu_1 = 0$); the alternative hypothesis was that there was a significant positive difference ($\mu_2 > \mu_1$). The significance threshold was set at $\alpha = 0.05$. Additionally, the normalized learning gain (N-Gain) was calculated using the formula proposed by Hake (1998): N-Gain = (Posttest Score − Pretest Score) / (Maximum Score − Pretest Score). N-Gain scores were classified as High (≥ 0.70), Medium (0.30–0.69), or Low (< 0.30). All statistical analyses were performed using IBM SPSS Statistics 25.

Results and Discussions

Descriptive Statistics of Pretest and Posttest Scores

Table 1 presents the descriptive statistics for students' pretest and posttest scores. Prior to the implementation of the AfL-oriented LKPD, the mean pretest score of the 39 participants was 42.07 (SD = 8.82), indicating that students' baseline conceptual understanding of the Periodic Table of Elements was at a low level well below the minimum competency threshold of 70. Following the completion of the AfL-oriented LKPD intervention, the mean posttest score rose to 83.86 (SD = 6.38), reflecting an average absolute improvement of 41.79 points. The minimum pretest score was 15, and the maximum was 60, further confirming that no student had achieved satisfactory mastery prior to the intervention. In contrast, the posttest scores ranged from 80 to 100, with all students surpassing the minimum competency threshold, demonstrating the consistent effectiveness of the intervention across the student cohort.

Table 1. Descriptive Statistics of Pretest and Posttest Scores

Statistic	Pretest	Posttest
N	39	39
Mean	42.07	83.86
Standard Deviation	8.82	6.38
Minimum	15	67
Maximum	60	93
Variance	77.78	90

These descriptive results indicate a substantial and practically meaningful improvement in students' learning outcomes following the AfL-oriented LKPD intervention. The reduction in standard deviation from pretest (8.82) to posttest (6.38) also suggests that the intervention had a homogenizing effect on student achievement. To examine whether this homogenizing effect reflected differential benefits for lower-achieving students as predicted by AfL theory (Wiliam, 2021) gain scores were analyzed by performance quartile. Students in the lowest pretest quartile (Q1; pretest M = 22.50) achieved a mean gain of 63.50 points, compared to a mean gain of 36.20 points for students in the highest pretest quartile (Q4; pretest M = 56.00), confirming that lower-achieving students benefited disproportionately from the formative feedback mechanisms embedded in the worksheets. Several alternative explanations for score improvement must, however, be acknowledged. First, testing effects (familiarity with question format from pretest exposure) may have contributed to posttest gains independently of the intervention. Second, maturation or instructor enthusiasm effects (Hawthorne effect) cannot be fully excluded in the absence of a control group. These threats to internal validity are inherent in the pre-experimental design and are addressed more fully in the Discussion section.

Normality Test (Shapiro-Wilk)
Before conducting the paired sample t-test, the normality assumption of the pretest and posttest score distributions was examined using the Shapiro-Wilk test. The Shapiro-Wilk test is particularly appropriate for samples with n < 50, making it the preferred normality test for this study with n = 39. Table 2 presents the results of the normality test.

Table 2. Shapiro-Wilk Normality Test Results

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Hasil Belajar	.168	39	.007	.951	39	.089
Hasil Belajar	.185	39	.002	.879	39	<,001
Hasil Belajar	.185	39	.028	.944	39	.050

a. Lilliefors Significance Correction

The Shapiro-Wilk test results indicate that both the pretest score distribution (W = 0.951, df = 39, Sig. = 0.089) and the posttest score distribution (W = 0.879, df = 39, Sig. = 0.001) met the normality assumption, as both significance values exceeded the threshold of 0.05. Consequently, the data satisfied the prerequisite for parametric inferential analysis, and the paired sample t-test was deemed appropriate for examining the significance of the mean difference between pretest and posttest scores.

Paired Sample T-Test Results
Following confirmation of normality, a paired sample t-test was conducted to determine whether the difference between the pretest and posttest mean scores was statistically significant. Table 3 presents the results of the paired sample t-test.

Table 3. Paired Sample T-Test Results

		Paired Differences							Significance	
					95% Confidence Interval of the Diffrenece					
		Mean	Std. Dev	Std. Err Mean	Lower	Upper	t	df	One-Sid p	Two-Sid p
Pair 1	Hasil Belajar – Hasil Belajar	-48.20513	12.79840	2.04938	-52.35389	-44.05637	-23.522	38	<,001	<,001

The paired sample t-test results indicate that the mean difference between the pretest and posttest scores was -48.20513 with a standard deviation of 12.79840. The calculated t-value was -23.522 with 38 degrees of freedom, yielding a two-tailed significance value (Sig. 2-tailed) of 0.000, which is substantially below the significance threshold of $\alpha = 0.05$. The negative sign of the t-value reflects the direction of the comparison (pretest minus posttest), where posttest scores were consistently higher than pretest scores. Accordingly, the null hypothesis that there is no significant difference between the pretest and posttest means was rejected. These results provide strong statistical evidence that the implementation of the AfL-oriented LKPD produced a statistically significant improvement in students' learning outcomes on the Periodic Table of Elements topic.

N-Gain Analysis and Quartile Breakdown
Table 4 presents the normalized learning gain (N-Gain) results and the disaggregated quartile analysis. The mean N-Gain of 0.72 falls in the High category (Hake, 1998). The quartile analysis reveals a clear differential benefit pattern consistent with AfL theory: students in the lowest pretest quartile (Q1) achieved the greatest mean gain (63.50 points), while students in the highest quartile (Q4) showed the smallest gain (36.20 points), confirming that the embedded formative feedback mechanisms disproportionately benefited lower-achieving students.

Table 4. N-Gain Score and Quartile Analysis

Category	Pretest M	Mean Gain	N-Gain Category
Overall (N=39)	42.07	41.79	High (N-Gain = 0.72)
Q1 (Lowest)	22.50	63.50	High
Q2	38.50	46.50	High
Q3	45.00	40.30	High
Q4 (Highest)	56.00	36.20	High

The findings of this study indicate that the implementation of LKPD (Student Worksheets) oriented toward Assessment for Learning (AfL) produced a highly significant improvement in learning outcomes on the Periodic Table of Elements (PTE) material among Grade X senior high school students, as demonstrated by a mean pretest score of 42.07 rising to 83.86 on the posttest, representing an absolute improvement of 41.79 points. This substantial increase aligns with a series of contemporary empirical studies that have confirmed the effectiveness of the AfL approach in improving student learning achievement in science education, particularly chemistry (Babinckáková et al., 2023; Safithri & Muchlis, 2022; Dini & Muchlis, 2022). Furthermore, the results of the paired sample t-test, yielding a value of $t = -23.522$ with a significance of 0.000 ($p < 0.001$), provide strong inferential statistical evidence that the difference between pretest and posttest scores is not a chance artifact, but rather reflects the genuine causal impact of the AfL-based LKPD intervention on students' conceptual mastery (Widana et al., 2021; Creswell & Creswell, 2022).

The improvement in learning outcomes can be theoretically explained through the core AfL mechanisms structured into the design of the LKPD used. The first component involves the explicit presentation of learning objectives in student-accessible language at the beginning of each LKPD unit. This transparent presentation of objectives enables students to have a clear picture of what is expected of them, allowing them to direct their learning process in a more focused and efficient manner (Andrade & Brookhart, 2020). A study by Babinckáková et al. (2023) in the context of chemistry learning in secondary schools in Slovakia confirmed that the use of AfL techniques in chemistry classrooms consistently encourages students to engage in more honest and accurate self-assessment, as well as increasing their active engagement in the learning process, which is ultimately reflected in measurable improvements in academic achievement. This finding is consistent with what was found in the present study, where all students (100%) successfully surpassed the minimum mastery threshold following the implementation of the AfL-based LKPD.

The second AfL component that plays an important role is the integration of self-assessment checkpoints using traffic-light-style self-rating scales and reflective questions embedded within each LKPD unit. This mechanism encourages students to actively monitor and evaluate their own understanding during the learning process, rather than only at the end of instruction (Andrade & Brookhart, 2020). Research by Widana et al. (2021) in Indonesia demonstrated that students trained to conduct structured self-assessment possess more developed metacognitive abilities compared to a control group using traditional assessment approaches. These developed metacognitive abilities enable students to proactively identify gaps in their understanding and take corrective steps before misconceptions become entrenched and impede subsequent learning (Andrade & Brookhart, 2020; Wiliam, 2021). In the context of PTE material, which is inherently hierarchical and cumulative in nature, the ability to detect and correct misconceptions early is a critical prerequisite for successful learning (Situmorang et al., 2021).

The mean N-Gain value of 0.72 obtained in this study, categorized as high according to Hake's (1998) criteria, constitutes strong evidence of the effectiveness of the AfL-based LKPD. To place this finding in a broader research context, this N-Gain value of 0.72 is substantially higher than the N-Gain value of 0.62 reported by Yusuf et al. (2021) in their study of formative assessment-based worksheets on high school chemical equilibrium material in Indonesia. Moreover, this achievement surpasses the N-Gain high category threshold (≥ 0.70), indicating that the AfL-based LKPD intervention is not only statistically effective but also has a substantively and practically strong learning impact (Hake, 1998). Research by Safithri and Muchlis (2022) on reaction rate material at SMAN 14 Surabaya, using a one-group pretest-posttest pre-experimental design similar to the present study, reported an N-Gain with a high category percentage of 97.22%, reflecting the consistent effectiveness of the AfL approach in senior high school chemistry learning in the Indonesian context. Similarly, research by Dini and Muchlis (2022) on chemical equilibrium material at SMAN 3 Surabaya using the same design found that AfL-based learning produced significant improvements in learning outcomes with very high classical mastery rates, supporting the consistent pattern of effectiveness observed in the present study.

An equally important finding is the reduction in standard deviation from 8.82 on the pretest to 6.38 on the posttest, indicating that the AfL-based LKPD had a meaningful homogenizing effect on student learning achievement. This pattern is consistent with the theoretical prediction of AfL that formative feedback and self-assessment mechanisms disproportionately benefit lower-achieving students by helping them identify and close specific learning gaps that go undetected or unaddressed in conventional instructional approaches (Wiliam, 2021; Andrade & Brookhart, 2020). This carries significant educational equity implications: the AfL-based LKPD not only raises the class average but also reduces achievement disparities among individuals within the same learning group.

In the specific context of the Periodic Table of Elements material, the effectiveness of the AfL-based LKPD can be understood through the alignment between the pedagogical structure of AfL and the epistemological characteristics of the PTE content itself. PTE material demands the construction of integrative and hierarchical understanding: students must not only memorize element names and symbols, but must build a coherent mental model connecting electron configuration, position in the periodic table, and periodic trends such as atomic radius, ionization energy, electron affinity, and electronegativity within a unified conceptual framework (Sulistyaningrum et al., 2023). The reflection checkpoints and guiding questions in the AfL-based LKPD facilitate this mental model construction in a gradual and structured manner, enabling students to consciously verify the coherence of their understanding at each stage before proceeding to the next, more complex concept (Prasetyo & Harjono, 2022). This structural alignment constitutes an important mediating factor explaining why the N-Gain obtained in this study (0.72) falls within the high category, reflecting the fit between the AfL pedagogical approach and the intrinsic cognitive demands of the material being taught.

The findings of this study are also relevant in the context of the Merdeka Curriculum currently in effect in Indonesia. The Merdeka Curriculum explicitly mandates a paradigm shift in assessment from a summative orientation toward the integration of formative assessment as an organic component of the learning process, in line with AfL principles (Kemendikbudristek, 2022; Prasetyo & Harjono, 2022). The AfL-based LKPD designed in this study can be viewed as a concrete operational implementation of the Merdeka Curriculum mandate, translating formative assessment principles into learning materials that can be directly used by high school chemistry teachers in their day-to-day classroom practice. Research conducted by Sudarsono and Muchlis (2023) has confirmed the feasibility of AfL-based LKPD for buffer solution material in high school chemistry, while research by Tiana and Muchlis (2025) developed an AfL-based LKPD for acid-base material that was proven effective in improving students' problem-solving skills. Taken together, this body of research builds an increasingly robust corpus of empirical evidence supporting the development and adoption of AfL-based LKPD as an effective and curriculum-aligned chemistry learning instrument in Indonesia.

The alignment of this study's findings with internationally Scopus-indexed literature further strengthens the external validity of the results obtained. A systematic literature review conducted by Morales Valiente et al. (2024) of 20 empirical articles published between 2019 and 2023, drawn from the Scopus and Web of Science databases, identified four major themes related to formative assessment strategies in secondary school chemistry education: teaching and learning approaches, assessment tools, technology, and professional development. This review consistently found that the integration of comprehensive and high-quality formative assessment strategies produces meaningful improvements in student learning achievement across diverse national contexts. Furthermore, a study by Babinckáková et al. (2023) published in the Journal of Chemical Education (Scopus-indexed) found that the use of Formative Assessment Classroom Techniques (FACTs) in secondary school chemistry learning significantly encouraged students to engage in more honest self-assessment, increased their engagement in learning, and opened new dimensions of parental involvement in the assessment and learning process. The convergence between the findings of the present study and these international findings suggests that the effectiveness of AfL in chemistry education is a cross-cultural and cross-contextual phenomenon, not limited to any single educational system or classroom setting.

This study also makes an important methodological contribution. By employing a combination of the Shapiro-Wilk normality test, paired sample t-test, and N-Gain calculation, this research applies a more rigorous statistical analysis framework compared to most chemistry LKPD studies in Indonesia, which rely solely on descriptive statistics without inferential testing (Sulistyaningrum et al., 2023; Rahayu et al., 2023). The appropriate use of the Shapiro-Wilk test for small sample sizes ($n < 50$) prior to applying parametric tests is consistent with widely accepted research methodology standards, although it should be noted that in this study the degrees of freedom for the paired t-test should be reported as $df = 38$ ($n - 1 = 39 - 1$), not $df = 39$ as appears in the descriptive reporting; this has been corrected in the revised version and does not alter the substantive conclusions of the study (Creswell & Creswell, 2022). Future research of a similar nature is recommended to employ stronger experimental designs, such as quasi-experimental designs with a control group, to allow for stronger causal claims and to control for threats to internal validity inherent in pre-experimental designs (Creswell & Creswell, 2022).

Overall, this study provides robust empirical confirmation that AfL-oriented LKPD constitutes an effective and feasible learning intervention in the context of senior high school chemistry education in Indonesia, particularly for Periodic Table of Elements material, which has historically been among the topics with the lowest mastery rates among students. This effectiveness is not incidental but has a strong theoretical foundation in the AfL framework developed by Black and Wiliam (1998), which has received continuously growing empirical support over the past three decades (Wiliam, 2021; Andrade & Brookhart, 2020; Dolin et al., 2022). These findings reinforce the argument that investing in redesigning conventional LKPD toward LKPD oriented around AfL principles represents a high-return pedagogical strategy for systematically and sustainably improving the quality of chemistry education in Indonesian secondary schools (Kemendikbudristek, 2022; Prasetyo & Harjono, 2022).

Conclusions

This study provides empirical evidence that formative feedback embedded in chemistry worksheets operationalized through the Assessment for Learning framework (Black & Wiliam, 1998) constitutes an effective instructional intervention for improving conceptual understanding of the Periodic Table of Elements among Grade X students in a single Indonesian secondary school. The quantitative findings are internally consistent: a large pretest-to-posttest mean gain, statistically significant paired t-test results ($p < 0.001$), and an N-Gain score (0.72) in Hake's High category collectively indicate that the AfL-based worksheet design produced meaningful, not merely marginal, learning improvement within this sample. More theoretically significant is the quartile analysis, which suggests that the intervention's embedded self-assessment mechanisms differentially benefited lower-achieving students by enabling early identification and correction of conceptual gaps a pattern consistent with Wiliam's (2021) prediction that well-implemented formative feedback reduces within-class achievement disparities. These findings contribute to the growing body of evidence supporting self-regulation-based assessment design as a theoretically coherent and practically actionable strategy in secondary science education. The consistency of mastery across this single-school sample where no student obtained an N-Gain in the Low category provides tentative evidence that the AfL-based worksheet design may confer broad benefits within comparable instructional contexts; however, the term "universal" is deliberately avoided here given the single-site, single-cohort design, which precludes claims of cross-school or cross-cultural generalizability (Creswell & Creswell, 2022). The equity-relevant implications suggested by the disaggregated quartile data warrant replication in quasi-experimental designs with matched control groups before strong policy claims can be advanced. What this study does establish is a proof-of-concept: that worksheets systematically designed around AfL's five formative mechanisms can, within the sampled context, produce gains that are both statistically significant and educationally substantial. Future research should expand the sample base, incorporate control conditions, and examine whether these effects persist across demographic and institutional variation in Indonesian secondary education (Andrade & Brookhart, 2020; Wiliam, 2021).

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