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The Influence of Zinc Supplementation on Improving Learning Concentration and Hemoglobin Levels in Anemic Adolescent Girls at Junior High School

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Abstract

Mild to moderate anemia impairs cognitive performance and academic engagement among adolescent girls, yet school-based nutrition programs in Indonesia focus largely on iron and vitamin A. This study evaluated whether a focused 30-day regimen of 20 mg/day zinc could improve both hemoglobin concentration and attention, as measured by the Stroop Color–Word Test, in 30 junior high school girls with baseline hemoglobin < 12 g/dL. Following daily supplementation, mean hemoglobin rose from 10.6 ± 0.5 g/dL to 12.4 ± 0.4 g/dL (Δ = 1.8 g/dL, p < 0.001, Cohen's d = 3.86), fully eliminating moderate anemia in this cohort. Stroop scores increased from 61.2 ± 5.3 to 75.8 ± 4.6 points (Δ = 14.6, p < 0.001, Cohen's d = 2.88), with no students remaining in the lowest concentration category post-intervention. These parallel gains reflect zinc's dual role in enhancing erythropoiesis improving cerebral oxygen delivery and modulating neurotransmission via NMDA/GABA balance and BDNF upregulation. Effect sizes exceed those typically reported for iron-only or broader micronutrient interventions. Findings support integrating a one-month zinc supplement into Indonesian school-health protocols to rapidly correct anemia and bolster cognitive readiness for learning.

Keywords: Zinc Supplementation; Adolescent Anemia; Hemoglobin; Stroop Color Word Test; Cognitive Concentration

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INTRODUCTION

Anemia remains a pressing public health concern in Indonesia, particularly among adolescent girls. According to the 2018 Basic Health Research Survey (Riskesdas), the prevalence of anemia in Indonesians aged 15–24 years was 32%, with the highest rates observed in females (Riskesdas, 2018). Adolescence represents a period of rapid growth and increased nutritional demands; when inadequate nutrient intake fails to meet these needs, mild to moderate anemia can ensue, manifesting as fatigue, diminished attention, and impaired school performance (World Health Organization [WHO], 2021). Beyond iron deficiency the most commonly cited cause of anemia suboptimal intake of other micronutrients such as zinc, along with poor dietary practices, contributes meaningfully to the burden of anemia in this group.

Adolescent anemia is not unique to Indonesia. Globally, roughly 27% of adolescents are anemic, with Southeast Asia bearing a disproportionate share of this burden (Pries et al., 2024;

Pai et al., 2023). In some settings, prevalence rates among school-aged girls soar as high as 65% (Syswianti & Roslan, 2024). For instance, a meta-analysis in Bangladesh reported a 37.7% anemia prevalence among children and adolescents (Kundu et al., 2023; Rahman et al., 2024), while in Nepal, Ghimire et al. (2024) documented rates near 50% among schoolgirls. These high prevalence figures reflect a complex interplay of factors dietary transitions toward energy-dense, nutrient-poor foods (Pries et al., 2024), socio-economic constraints on accessing iron-rich diets (Yusufu et al., 2023), and biological changes of puberty that elevate nutritional requirements (Pai et al., 2023).

Educational interventions have demonstrated promise in raising awareness and improving compliance with iron and folic acid supplementation. In Indonesia, school-based health education campaigns increased adolescent girls' understanding of anemia and adherence to supplementation regimens (Yanisah & Widati, 2023; Adlu & Fayasari, 2023). Syswianti and Roslan (2024) similarly found that targeted education bolstered compliance rates with iron–folic acid programs. Yet, despite these gains, iron-only strategies may fall short: emerging evidence suggests that co-supplementation with zinc enhances both hematological and cognitive outcomes compared to iron alone (Yuliani & Hartati, 2022).

Zinc is an essential trace element involved in over 300 enzymatic reactions, among them those critical for growth, immune function, and neurological development (Black, 2019). In neurophysiology, zinc modulates key neurotransmitter systems. It regulates glutamatergic and GABAergic signaling by influencing NMDA receptor activity and synaptic plasticity processes vital for attention, memory consolidation, and learning (Huang et al., 2023; Starowicz et al., 2023; Zielińska et al., 2023). Zinc deficiency can disrupt these pathways, reducing brain-derived neurotrophic factor (BDNF) activity and impairing neurogenesis, with downstream effects on cognition and mood (Padoan et al., 2024).

Beyond its neural roles, zinc supports erythropoiesis and hemoglobin synthesis. It acts as a cofactor for enzymes involved in heme metabolism and stabilizes red blood cell membranes against oxidative damage (Kuang et al., 2023; Vargas et al., 2023). Clinical studies link improved zinc status to rises in hemoglobin concentration and red blood cell counts, especially in populations with baseline deficiencies (Ismael et al., 2024). In adolescent girls who face increased iron requirements during growth and menstrual blood loss zinc's dual role in oxygen transport and cognitive function makes it a compelling target for supplementation.

In Indonesia, the School Health Unit (Unit Kesehatan Sekolah, UKS) traditionally emphasizes iron and vitamin A supplementation, with less systematic implementation of zinc programs. The Ministry of Health's guidelines recommend biweekly iron folic acid supplementation for adolescent girls, alongside nutritional education, yet zinc is only peripherally addressed (Silitonga et al., 2023). Comparative analyses across Southeast Asia reveal a spectrum of strategies: Thailand and Vietnam pair weekly iron folate regimens with comprehensive dietary education (Cliffer et al., 2023), while Bangladesh's WIFAS (weekly iron–folic acid supplementation) programs have encountered challenges in adherence due to cultural and logistical barriers (Kedir et al., 2024).

Zinc supplementation policies lag behind iron initiatives. In Indonesia, pilot community-based models engage parents and local health cadres to distribute zinc, improving compliance modestly (Atmadani et al., 2024; Silitonga et al., 2023). The Philippines has experimented with fortified snacks and direct school-based zinc distribution, yielding promising reductions in deficiency markers but encountering logistical hurdles in supply chain management (Rai et al., 2024; Hussain, 2023). Common challenges across the region include securing a reliable supply of zinc tablets, cultural perceptions that undervalue mineral supplements, and limited budget allocation for micronutrient programs (Totten et al., 2023).

Meta-analyses and randomized controlled trials provide mixed but encouraging data on zinc's efficacy. A pilot study in rural Bangladesh observed positive correlations between serum zinc and Stroop test performance among adolescents (Rahi et al., 2024). In Indonesia, Smith et al. (2020) reported that zinc supplementation improved attention scores in nutritionally at-risk teens. Yet, heterogeneity in dose, duration, and baseline zinc status complicates interpretation: some trials demonstrate significant cognitive gains only at doses ≥20 mg/day over periods longer than four weeks, whereas shorter or lower-dose regimens yield minimal effects (Mozaffar et al., 2023; Syswianti & Roslan, 2024).

Regarding hemoglobin, meta-analytic data indicate that zinc co-supplementation with iron produces larger hemoglobin increases than iron alone, with effect sizes in the moderate to large range (Kristyani et al., 2024; Romaña et al., 2023). These gains likely reflect zinc's facilitation of iron absorption and its support of red cell stability. In a recent Indonesian school-based trial, girls receiving combined zinc–iron supplements saw mean hemoglobin rises of 1.5 g/dL after six weeks, versus 0.9 g/dL in the iron-only group (Yuliani & Hartati, 2022).

Despite mounting evidence, critical gaps remain. First, few studies have simultaneously assessed hematological and cognitive endpoints within the same adolescent cohort using standardized neurocognitive tools such as the Stroop Color Word Test. Second, research specifically on 20 mg/day zinc for 30 days is scarce, and no trial to date has paired this regimen with hemoglobin monitoring and Stroop-based concentration measures in Indonesian junior high settings. Third, many published trials lack clear theoretical framing around zinc's mechanistic pathways in neurotransmission and erythropoiesis, or they omit discussion of contextual factors such as dietary patterns, menstrual status, and socio-economic influences that may modulate outcomes (Berger & Shenkin, 2024; Meijer et al., 2024).

To address these gaps, the current study employs a one-group pretest–posttest design in a cohort of junior high school girls with mild to moderate anemia (hemoglobin < 12 g/dL). The specific aims are: 1) Hematological Impact To determine whether 30 days of zinc supplementation at 20 mg/day yields a statistically significant increase in hemoglobin concentration, 2) Cognitive Outcomes To evaluate changes in learning concentration measured via response time and accuracy on the Stroop Color Word Test before and after supplementation, 3) Integrated Effect To examine the relationship between hemoglobin improvements and concentration gains, testing whether zinc's hematological benefits parallel enhancements in cognitive function.

Findings will offer empirical support for incorporating zinc into school health policies and will inform the design of holistic interventions that align nutritional and educational objectives. By situating zinc within both mechanistic and policy frameworks, this study seeks to strengthen the scientific basis for co-supplementation programs in Indonesian schools and contribute to broader Southeast Asian efforts to combat adolescent anemia and its cognitive sequelae.

METHOD

This study employed a one-group pretest–posttest quasi-experimental design to evaluate the impact of zinc supplementation on hemoglobin levels and learning concentration in adolescent girls . Without a separate control arm, this approach measures within-subject changes attributable to the intervention while accounting for baseline variability. Such designs are well suited to school-based health initiatives where withholding treatment may be unethical.

Participants and Setting

The research took place at a public junior high school in Surabaya, selected for its active collaboration with the local community health center's School Health Unit (UKS) and availability of recent anemia screening data. Female students aged 12–15 years with hemoglobin < 12 g/dL, willing to take a daily 20 mg zinc tablet for 30 days, and not currently on other micronutrient supplements were recruited via purposive sampling (Sugiyono, 2021). From an initial pool of 52 eligible students, 30 consented and completed the study, ensuring adequate power ($\alpha = 0.05$, 80% power) to detect medium-to-large effect sizes.

Intervention Procedure

Participants received 20 mg elemental zinc in tablet form each morning for 30 consecutive days, supervised by UKS personnel to maximize adherence. Prior to supplementation, all girls underwent baseline assessments: hemoglobin measurement using a portable digital hemoglobinometer (validated for field settings) and cognitive testing with the Indonesian-adapted Stroop Color–Word Test (SCWT). The SCWT, a robust measure of executive function and inhibitory control, has demonstrated strong validity and reliability across adolescent populations (Park et al., 2023; Guo et al., 2023). Thirty days post-intervention, hemoglobin and SCWT were reassessed under identical conditions.

Instruments and Data Collection

Hemoglobin levels were captured via a digital hemoglobinometer, offering point-of-care accuracy (Ismael et al., 2024). Learning concentration was quantified using two complementary SCWT metrics: response time (measured with a stopwatch) and accuracy (number of correct color–word alignments within a fixed interval). Teacher observations of class engagement frequency of questions asked and responses given provided behavioral triangulation of cognitive performance.

A demographic and health-history questionnaire, validated by a public-health expert, collected age, height, weight, menstrual status, and anemia history. Content validity for all instruments was confirmed by a panel of three specialists (nutritionist, education expert, child-psychology expert). Reliability testing on a pilot group ($n = 20$) yielded Cronbach's $\alpha > 0.7$ for cognitive measures and questionnaire scales, indicating internal consistency (Arikunto, 2019).

Ethical Considerations

The study protocol received approval from the university's ethics committee. Parental consent and participant assent were obtained in writing. All data were anonymized, and participants could withdraw at any time without penalty.

Data Analysis

Normality of pretest and posttest distributions was verified with Kolmogorov–Smirnov tests (all $p > 0.05$), permitting parametric analyses. Paired-sample t-tests compared mean hemoglobin and SCWT scores before and after supplementation, with effect sizes calculated using Cohen's d. A significance threshold of $p < 0.05$ was applied. Analyses were conducted in SPSS v26.

Table 1. Summary of Analysis Methods

Variable	Pretest Normality (p)	Posttest Normality (p)	Test	Effect Size Metric
Hemoglobin (g/dL)	0.167	0.200	Paired t-test	Cohen's d
Stroop Response Time	0.112	0.175		Cohen's d
Stroop Accuracy Score	0.112	0.175		Cohen's d

Quality Control and Limitations

To ensure intervention fidelity, UKS staff supervised daily intake and recorded missed doses. Testing environments were standardized: quiet rooms for SCWT, same time of day for hemoglobinometry, and identical procedural instructions. Limitations include the absence of a control group and potential seasonal or curricular influences; future work should incorporate randomized, multi-site designs with dietary and menstrual status logs to refine causal inferences.

By combining physiological measurement with validated cognitive assessment and behavioral observation, this method captures a comprehensive picture of zinc's dual impact on adolescent health and learning readiness, in line with recent quasi-experimental studies of educational interventions (Pan et al., 2024; Tonkaz & Çayır, 2024).

RESULTS AND DISCUSSION

The present study examined the effects of thirty consecutive days of zinc supplementation (20 mg/day) on both hematological status and learning concentration among thirty mildly anemic junior high school girls (hemoglobin < 12 g/dL). Hemoglobin was measured via digital hemoglobinometry, and concentration was assessed using the Stroop Color Word Test (response time and accuracy). Teacher-reported engagement provided qualitative context. Data were normally distributed (Kolmogorov–Smirnov p > 0.05 for all variables), permitting parametric analyses.

Hematological Recovery

Mean hemoglobin concentration rose from 10.6 ± 0.5 g/dL at pretest to 12.4 ± 0.4 g/dL posttest, a mean increase of 1.8 g/dL (paired t = –…, p < 0.001) (Table 1). Cohen's d of 3.86 indicates a very large effect (Table 5). This improvement exceeds the 1.2 g/dL average gain reported in a recent meta-analysis of zinc–iron co-supplementation trials (Kristyani et al., 2024), and aligns with findings in chronic-kidney-disease patients, where adjunct zinc raised hemoglobin by 1.5 g/dL over twelve weeks (Nazari et al., 2023).

Table 2. Hemoglobin Levels Before and After Zinc Supplementation

Variabel	Pretest (Mean ± SD)	Posttest (Mean ± SD)	Difference	p-value (t-test)
Hemoglobin Level (g/dL)	10.6 ± 0.5	12.4 ± 0.4	+1.8	< 0.001

Table 2 demonstrates a significant increase in hemoglobin levels among participants following zinc supplementation. The mean hemoglobin level rose from 10.6 ± 0.5 g/dL at pretest to 12.4 ± 0.4 g/dL at posttest, reflecting a mean increase of 1.8 g/dL. The p-value < 0.001 from the paired *t*-test indicates that this improvement is statistically significant. This increase suggests a robust physiological response to zinc supplementation in adolescents with anemia, potentially due to zinc's multifaceted role in hematological processes.

Zinc contributes critically to hemoglobin synthesis by functioning as a cofactor for enzymes involved in heme biosynthesis, particularly δ-aminolevulinic acid dehydratase. This enzyme catalyzes a key early step in the formation of protoporphyrin IX, into which iron is later incorporated to form heme, the functional component of hemoglobin (Kuang et al., 2023). In this biochemical context, zinc facilitates the efficient utilization of iron, enhancing erythropoiesis and red blood cell function.

Additionally, zinc's role as a powerful antioxidant further supports its hematological benefits. By stabilizing erythrocyte membranes and reducing oxidative stress, zinc decreases the rate of hemolysis, or premature red blood cell breakdown (Vargas et al., 2023). This protective effect is especially relevant in adolescent populations vulnerable to micronutrient deficiencies and oxidative damage due to growth spurts and poor dietary intake.

The hematological benefits of zinc are not limited to adolescent populations. A clinical study by Nazari et al. (2023) involving patients with chronic kidney disease (CKD) showed that adjusting zinc intake to meet recommended dietary intake (RDI) levels significantly improved hemoglobin concentrations. Interestingly, this effect was observed in conjunction with improved serum copper levels, underscoring the delicate interplay between trace elements in effective anemia management. These findings suggest that zinc supplementation should be carefully calibrated to avoid imbalances that might otherwise impair iron metabolism.

Similarly, Sari et al. (2024) reported enhanced hemoglobin levels in thalassemia patients following zinc supplementation, attributed largely to the improved management of oxidative stress and restoration of serum zinc concentrations. These findings affirm that zinc plays a systemic role in improving hematological health, not only by supporting hemoglobin synthesis but also by enhancing red cell integrity under oxidative duress.

In another related study, Seirafian et al. (2023) focused on patients undergoing hemodialysis a group often suffering from anemia due to erythropoietin resistance. Zinc supplementation in this population resulted in higher hemoglobin levels and a reduced requirement for erythropoiesis-stimulating agents. This suggests that zinc may help restore responsiveness to such therapies or serve as a complementary approach to improve hematological outcomes.

The interaction between zinc and copper was also highlighted in Takahashi’s (2023) review, which emphasized the importance of maintaining a balanced ratio between these trace elements. Copper plays a critical role in iron mobilization and oxidation; hence, unregulated zinc supplementation could inadvertently disrupt copper metabolism and impair hemoglobin synthesis. This finding reinforces the need for individualized micronutrient assessments and supplementation strategies.

Mechanistically, zinc influences erythropoiesis through its regulation of transcription factors, such as GATA-1 a zinc finger protein essential for red blood cell development (Inoue, 2024). This molecular insight suggests that beyond being a structural component, zinc actively regulates gene expression involved in erythroid lineage maturation, adding another dimension to its importance in managing anemia.

A study by Fukasawa et al. (2024) emphasized the long-term health benefits of zinc supplementation in at-risk populations, including those with dietary limitations. Their findings align with the growing consensus that zinc should be recognized as a key micronutrient in anemia prevention and treatment strategies.

The evidence from this study and existing literature strongly supports the efficacy of zinc supplementation in improving hemoglobin levels, especially among adolescents. Given its role in enzymatic activity, antioxidant defense, and gene regulation, zinc stands out as a valuable intervention for anemia, provided that supplementation is administered with consideration of individual nutritional status and potential micronutrient interactions.

Shifts in Anemia Categories

The proportion of participants with moderate anemia (< 10 g/dL) fell from 13.3 percent at baseline to zero post-supplementation; those with mild anemia (10.0–10.9 g/dL) dropped from 53.3 percent to 6.7 percent. Conversely, individuals achieving normal hemoglobin levels (≥ 12 g/dL) increased dramatically from 6.7 percent to 76.6 percent.

Table 3. Frequency Distribution of Hemoglobin Levels (g/dL)

Hemoglobin Range	Pretest (n, %)	Posttest (n, %)
< 10.0	4 (13.3 %)	0 (0.0 %)
10.0–10.9	16 (53.3 %)	2 (6.7 %)
11.0–11.9	8 (26.7 %)	5 (16.7 %)
≥ 12.0	2 (6.7 %)	23 (76.6 %)
Total	30 (100 %)	30 (100 %)

Table 3 illustrates a substantial categorical shift in hemoglobin levels among adolescent girls before and after zinc supplementation. At the pretest stage, the majority of participants fell within the low hemoglobin ranges: 13.3% (n=4) had levels below 10.0 g/dL, while 53.3% (n=16) were in the 10.0–10.9 g/dL range. Only 6.7% (n=2) had hemoglobin levels at or above 12.0 g/dL. After supplementation, the distribution dramatically shifted, with 76.6% (n=23) achieving hemoglobin levels ≥12.0 g/dL, and no participants remaining in the <10.0 g/dL category. This represents not only a statistically significant change but also a clinically meaningful improvement in hematological status.

Such a transformation underscores the therapeutic potential of zinc in addressing anemia. The elimination of moderate anemia cases and normalization of hemoglobin in three-quarters of the participants mirrors findings from community-based studies. Notably, a study in Pakistan by Khan et al. (2023) reported that long-term zinc supplementation increased the proportion of individuals with normal hemoglobin from 20% to 68%, emphasizing zinc's role in large-scale public health interventions.

Although zinc is not a direct substitute for iron, it plays a complementary and essential role in erythropoiesis. Zinc is a cofactor in key enzymes involved in heme biosynthesis and also stabilizes red blood cell membranes by mitigating oxidative stress, thereby reducing hemolysis. When administered in zinc-deficient or anemic populations, supplementation supports both red blood cell production and longevity.

Several studies support the idea that micronutrient-based interventions, particularly those involving iron and other trace elements, yield significant hematologic benefits. For example, Rakanita et al. (2023) showed that one month of iron supplementation led to an average increase of 2.00 g/dL in hemoglobin among anemic women of reproductive age. Similarly, Wahyuni et al. (2023) demonstrated that pregnant women who consumed boiled eggs daily saw increases in hemoglobin levels from 9.21 g/dL to 10.99 g/dL, reinforcing the notion that food-based nutritional interventions can enhance hemoglobin status effectively.

Other micronutrients also contribute to improved hemoglobin outcomes. A systematic review by Ahmad et al. (2023) found that vitamin D supplementation may enhance hemoglobin levels among chronic kidney disease patients undergoing hemodialysis, although further research is needed to clarify its direct mechanisms. Meilani and Setiyawati (2023) highlighted that adherence to iron supplementation correlated positively with hemoglobin improvements, underscoring the importance of consistency in treatment.

Ghannam et al. (2023) conducted a quasi-experimental study comparing iron supplementation alone to a combination of iron and vitamin B6 in pregnant women with iron deficiency anemia. Both groups showed hemoglobin improvements, but the combined approach yielded slightly better outcomes. This supports the value of multifactorial supplementation strategies in managing anemia.

Dietary interventions have also proven effective. Fikawati and Syafiq (2023) documented significant hemoglobin increases among pregnant women and adolescents following fortified milk supplementation. Similarly, studies by Ratnaningsih et al. (2024) and Park et al. (2023) found that specific dietary components such as legumes and fortified foods helped raise hemoglobin levels in at-risk populations.

These findings emphasize the multifaceted nature of anemia treatment. While iron remains the cornerstone of most interventions, zinc supplementation particularly in populations with marginal zinc status offers an important adjunct therapy. The marked shift in hemoglobin distribution post-intervention in this study adds to the growing body of evidence supporting the integration of zinc into anemia management protocols, especially for adolescent girls who are particularly vulnerable to micronutrient deficiencies and related hematologic disorders.

Cognitive Concentration Enhancement

Zinc supplementation produced a striking improvement in students' ability to sustain attention, as measured by the Stroop Color–Word Test. Before supplementation, participants averaged 61.2 (± 5.3) on the concentration metric; after thirty days of daily 20 mg zinc, their score rose to 75.8 (± 4.6), an increase of 14.6 points ($p < 0.001$). The calculated Cohen's d of 2.88 places this effect well beyond the "large" threshold most nutrition-cognition trials report d values between 0.5 and 1.0 highlighting an unusually robust response (Pilz-Burstein et al., 2023; Mozaffar et al., 2023).

Table 4. Stroop-Based Concentration Scores Before and After Zinc Supplementation

Variabel	Pretest (Mean ± SD)	Posttest (Mean ± SD)	Difference	p-value	Cohen's d
Concentration Learning Score	61.2 ± 5.3	75.8 ± 4.6	+ 14.6	< 0.001	2.88

Several mechanisms likely account for these gains. Zinc modulates excitatory (glutamatergic) and inhibitory (GABAergic) pathways by interacting with NMDA and GABA receptors in the prefrontal cortex and hippocampus regions critical for executive control and working memory (Huang et al., 2023; Starowicz et al., 2023). By fine-tuning synaptic plasticity, zinc enhances the brain's capacity to filter distractions and maintain goal-directed attention.

Beyond receptor-level effects, zinc upregulates brain-derived neurotrophic factor (BDNF), a protein that fosters neuronal growth and synaptic strengthening. Increased BDNF expression promotes neurogenesis and facilitates long-term potentiation, processes essential for both memory consolidation and rapid information processing (Padoan et al., 2024). Given that adolescents undergo significant neural remodeling, zinc's support of these pathways may be especially potent during this developmental window.

Meta-analytic evidence reinforces these findings. Reviews of micronutrient interventions in children and adolescents report that zinc supplementation yields meaningful improvements in tasks of selective attention and processing speed, with pooled Stroop gains of 8–10 points (Park et al., 2023; Romagnoli et al., 2024). Our 14.6-point jump suggests that directly targeting zinc deficiency rather than broader multivitamin regimens can produce more pronounced cognitive benefits, particularly when baseline zinc levels are low.

Improved hematological status likely contributed to the cognitive boost. As hemoglobin rose by 1.8 g/dL in this cohort, cerebral oxygen delivery would have increased, reducing mental fatigue and supporting sustained focus (Pai et al., 2023; Santosa et al., 2024). Teacher observations corroborated this: many students reported feeling less tired in afternoon lessons and demonstrated greater on-task behavior.

Finally, educational and community interventions that combine nutrition education with zinc distribution have shown enhanced compliance and amplified cognitive outcomes. For example, Engidaw et al. (2024) found that pairing zinc tablets with brief classroom lessons on healthy eating doubled adherence rates and led to superior attention scores compared to supplementation alone. Integrating similar strategies into school-based programs could further magnify the benefits demonstrated here.

The dramatic improvement in Stroop concentration scores underpinned by zinc's neuromodulatory actions, neurotrophic support, and hematological effects provides compelling evidence for including zinc in adolescent health and education initiatives. Such interventions promise not only to correct micronutrient deficiencies but also to enhance the very cognitive functions that underlie academic success.

Distribution of Concentration Levels

The redistribution of Stroop-based concentration scores following thirty days of zinc supplementation reveals a marked elevation in students' ability to sustain attention and process information rapidly. Prior to the intervention, one-third of participants (33.3 %) scored below 60 a range indicative of poor concentration. After supplementation, no student remained in that lowest bracket. Meanwhile, the proportion achieving mid-range scores (60–69) declined sharply from 46.7 % to 13.3 %, and those in the 70–79 band increased from 23.3 % to 60.0 %.

Most notably, a new high-performing subgroup emerged: 26.7 % of students scored 80 or above post-intervention, up from 0 % at baseline.

Table 5. Frequency Distribution of Stroop-Based Concentration Scores

Concentration Score	Pretest (n, %)	Posttest (n, %)
< 60	10 (33.3 %)	0 (0.0 %)
60–69	14 (46.7 %)	4 (13.3 %)
70–79	7 (23.3 %)	18 (60.0 %)
≥ 80	0 (0.0 %)	8 (26.7 %)
Total	30 (100 %)	30 (100 %)

This upward shift in category membership reflects two synergistic effects of zinc supplementation. First, improved processing speed: as more students moved into higher score bands, average response times on incongruent Stroop trials decreased, suggesting faster cognitive control. Second, enhanced selective attention: with fewer distractions and lapses, participants navigated color-word conflicts more efficiently.

Meta-analyses of micronutrient interventions provide context for these results. Iron–folate supplementation typically yields 8–10-point average improvements on Stroop tests in adolescent cohorts (Park et al., 2023; Romagnoli et al., 2024). The 14.6-point mean gain observed here—reflected in the dramatic category shifts suggests that addressing zinc deficiency directly may confer additional cognitive advantages beyond those seen with iron alone. Indeed, systematic reviews highlight zinc's unique role in modulating neurotransmitter systems critical for attention, including glutamatergic (NMDA) and GABAergic pathways, and in upregulating brain-derived neurotrophic factor (BDNF) to support synaptic plasticity (Huang et al., 2023; Padoan et al., 2024).

Improved hemoglobin status likely augmented these neurophysiological effects. As mean hemoglobin increased by 1.8 g/dL (Cohen's d = 3.86), cerebral oxygenation would have improved, reducing mental fatigue and enhancing overall alertness (Pai et al., 2023; Santosa et al., 2024). Teacher observations confirmed that students exhibited greater on-task behavior and reported feeling less exhausted during afternoon classes an educationally meaningful outcome given the well-documented link between anemia correction and academic performance (Putri, 2022).

Furthermore, community-based trials combining zinc distribution with brief nutrition education report doubled adherence and even larger concentration gains compared to supplementation alone (Engidaw et al., 2024). Embedding zinc tablets within a curriculum that explains their role in cognition and health may therefore magnify results. In rural Indonesian settings, parent-and-cadre led programs achieved over 80 % compliance and notable improvements in both hemoglobin and attention metrics (Atmadani et al., 2024).

To illustrate the robustness of these findings, Table 6 summarizes normality tests and effect-size metrics for both hemoglobin and concentration outcomes. All variables were normally distributed (Kolmogorov Smirnov $p > 0.05$), validating the use of parametric analyses. Effect sizes were exceptionally large, with Cohen's d values of 3.86 for hemoglobin and 2.88 for concentration far exceeding conventional "large" thresholds and underscoring zinc's potent impact in this demographic.

Table 6. Normality and Effect-Size Metrics

Variabel	Sig. Pretest	Sig. Posttest	Distribusi	Cohen's d	Effect Size
Hemoglobin Level	0.167	0.200	Normal	3.86	Very large
Concentration Score	0.112	0.175	Normal	2.88	Very large

These data suggest that a focused, thirty-day regimen of 20 mg/day zinc yields rapid and clinically meaningful gains in both physiological and neurocognitive domains for anemic adolescent girls. The pronounced shifts in concentration-score categories, coupled with corroborating hemoglobin improvements, advocate for expanding zinc supplementation within school-health programs. Integrating such interventions with supportive education on micronutrient roles could enhance students' capacity to engage and learn, ultimately contributing to improved educational outcomes in regions burdened by adolescent anemia.

The concurrent rises in hemoglobin and cognitive-attention scores among the adolescent girls in this study suggest that zinc exerts its benefits through two complementary avenues. On one hand, bolstered erythropoiesis increases hemoglobin concentration, enhancing oxygen delivery to the brain. Improved oxygenation reduces the pervasive tiredness that often accompanies anemia, allowing students to engage more fully and sustain focus in class an effect corroborated by teacher reports of greater on-task behavior and by studies linking higher hemoglobin with improved academic outcomes (Pai et al., 2023; Putri, 2022). On the other hand, zinc directly modulates neurotransmission: by fine-tuning NMDA and GABA receptor activity, it sharpens synaptic plasticity within the prefrontal cortex and hippocampus, key regions for executive control and working memory (Huang et al., 2023; Starowicz et al., 2023). Simultaneously, zinc upregulates brain-derived neurotrophic factor (BDNF), promoting neuron growth and reinforcing the synaptic connections that underlie rapid information processing and memory consolidation (Padoan et al., 2024). The tight relationship we observed between individual changes in hemoglobin and Stroop scores ($r = 0.72$, $p < 0.001$) underscores how these physiological and neural pathways intersect to enhance cognitive performance.

When compared with regional data, our findings stand out for both magnitude and rapidity. In Bangladesh, eight-week zinc–iron co-supplementation reduced anemia by roughly 20 percent and yielded Stroop improvements of about 12 points (Kundu et al., 2023; Rahman et al., 2024). In Nepal, similar interventions produced mean hemoglobin gains of 1.6 g/dL and cognitive enhancements averaging 10 points (Ghimire et al., 2024). The 30-day, zinc-only regimen in our Indonesian cohort delivered an even larger hemoglobin increase (1.8 g/dL) alongside a 14.6-point Stroop jump. These pronounced effects likely reflect the confluence of higher baseline zinc deficiencies in our population, the consistency afforded by school-based delivery, and the absence of iron's gastrointestinal side effects which can hamper adherence in co-supplementation programs (Engidaw et al., 2024).

At present, Indonesia's School Health Unit (Unit Kesehatan Sekolah, UKS) framework focuses on biweekly iron–folate dosing and general nutrition education, yet zinc remains conspicuously under-utilized despite evidence of its synergistic impact (Silitonga et al., 2023; Yuliani & Hartati, 2022). Introducing a one-month course of 20 mg elemental zinc per day into UKS protocols could strengthen anemia control and cognitive readiness at minimal extra cost. Pilot community models, engaging local health workers and parents to distribute zinc alongside iron, have achieved over 80 percent adherence and improved hemoglobin by nearly 0.9 g/dL in rural districts (Atmadani et al., 2024). Scaling such models school-wide would likely yield even greater dividends in attention and learning.

Beyond these practical considerations, a deeper mechanistic understanding could refine intervention strategies. Zinc's regulation of heme-oxygenase and ferroportin hints at roles in iron mobilization and recycling, potentially enhancing the efficiency of co-supplemented iron (Kuang et al., 2023). At synapses, zinc's control of vesicular zinc pools directly influences excitatory and inhibitory neurotransmitter release dynamics, shaping attentional networks (Bagaric et al., 2024). Future research should incorporate biomarkers such as serum ferritin, zinc protoporphyrin, and BDNF levels to quantitatively map these pathways. Randomized controlled trials that compare zinc alone, iron alone, and combined regimens across various regions would clarify optimal dosages and durations. Accounting for menstrual-cycle phases and dietary intake via detailed food-frequency questionnaires would further explain individual variability in response.

Nonetheless, our single-group pretest–posttest design limits causal inferences. External factors seasonal changes, concurrent deworming campaigns, or curricular shifts cannot be fully excluded. The study's confinement to one school also restricts generalizability. Despite reported adherence above 95 percent, unmeasured confounders such as vitamin A status or latent infections may have contributed to the observed improvements. Blinded, multi-site trials with longer follow-up periods are needed to confirm the durability of both hematological and cognitive gains.

These integrated results and discussion points emphasize that a brief, focused course of zinc supplementation can drive very large gains in both blood health and attentional capacity among anemic adolescents. By addressing zinc deficiency directly and perhaps more potently than broader multivitamin or iron-only approaches school-based programs can deliver rapid, clinically meaningful improvements in how students feel and learn. Given the inextricable link between nutritional status and educational achievement, embedding zinc into national school-health policies offers a scalable, evidence-based strategy for elevating both adolescent well-being and academic success in Indonesia and similar low-resource settings.

CONCLUSION

This study demonstrates that a focused, thirty-day course of zinc supplementation at 20 mg per day produces very large and rapid gains in both hematological health and cognitive concentration among mildly anemic adolescent girls. Hemoglobin levels rose on average by 1.8 g/dL eliminating moderate anemia entirely and normalizing hemoglobin in over three-quarters of participants while Stroop Color Word Test scores improved by 14.6 points, with a Cohen's d of 2.88 indicating an effect size well beyond those typically seen in nutritional-cognition research. These parallel improvements reflect zinc's dual actions: enhancing erythropoiesis and cerebral oxygen delivery, which alleviates fatigue and supports sustained attention, and modulating neurotransmission through NMDA/GABA balancing and upregulation of BDNF, which strengthens synaptic plasticity in executive networks. The strong correlation between individual hemoglobin and concentration gains underscores the interdependence of physiological and neurocognitive pathways. Compared to regional trialswhere eight-week zinc iron regimens yielded smaller hemoglobin and Stroop gains this one-month, zinc-only approach appears especially potent, likely owing to higher baseline deficiencies, school-based delivery ensuring high adherence, and avoidance of iron's gastrointestinal side effects. These findings provide compelling evidence that integrating zinc into school health initiatives can address adolescent anemia while directly enhancing the cognitive functions critical for learning.

RECOMMENDATIONS

Based on these results, we recommend that the Indonesian School Health Unit (UKS) incorporate a one-month, daily zinc supplementation protocol (20 mg elemental zinc) alongside existing iron–folate programs in junior high schools. Embedding zinc distribution within the school day facilitated by teachers or health cadres will capitalize on high adherence and minimize missed doses. To reinforce compliance and maximize impact, brief classroom sessions explaining zinc's roles in blood health and brain function should accompany supplement delivery. Policymakers should also consider piloting community-based distribution models that engage parents and local health workers, as these have demonstrated strong uptake and additional gains in rural settings. Future program evaluation should include biomarker monitoring (e.g., serum ferritin, zinc protoporphyrin, BDNF levels) and cognitive assessments to refine dosage and timing. Longer-term studies, ideally randomized and factorial in design, are needed to compare zinc alone, iron alone, and combined regimens, while controlling for menstrual-cycle phase and dietary intake. By integrating these recommendations, school-based nutrition strategies can swiftly reduce anemia prevalence and elevate students' capacity to focus, learn, and succeed academically.

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AUTHOR CONTRIBUTIONS

Sukma Sahadewa conceived and designed the study, supervised data collection, and led manuscript writing. Fara Disa Durry performed the statistical analyses, prepared figures and tables, and contributed to drafting the Results and Discussion. Nur Khamidah organized the intervention logistics, coordinated with the School Health Unit, and managed participant recruitment and follow-up. Novia Restu Windayani developed the cognitive assessment protocol, administered the Stroop Color Word Tests, and assisted with data interpretation.

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