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Assoc. Prof. Dr. Zukifli, M. Pd
Universitas Islam Riau

CORRESPONDENCE
Erna Lestari Rambe
ernalestarirambe@gmail.com

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Ergonomic Analysis in Optimizing Science Learning: Physical Environment Impact on Academic Performance

Erna Lestari Rambe*[1], Khairul Zikri[2], Dedi Nofrizal[3]

[1]STKIP Meranti, Indonesia.
[2]Sekolah Dasar Negeri 176 Pekanbaru, Riau, Indonesia.
[3]Fakultas Keguruan dan Ilmu Pendidikan, Universitas Pembinaan Masyarakat Indonesia, Indonesia.

ABSTRACT

Purpose of the study: This research investigates the relationship between classroom ergonomic conditions and science learning outcomes in elementary schools, aiming to identify optimal physical environmental factors that enhance student academic performance and teacher effectiveness in science education.
Materials and methods: A quantitative cross-sectional study was conducted involving 450 students and 45 teachers from 15 elementary schools in Pekanbaru City, Indonesia. Data collection utilized structured questionnaires measuring classroom design adequacy, ergonomic comfort levels, and their perceived impact on science learning. Statistical analysis was performed using SPSS version 29.0, employing descriptive statistics, correlation analysis, and multiple regression modeling.
Results: Significant positive correlations were found between ergonomic classroom conditions and science learning outcomes ($r = 0.742$, $p < 0.001$). Students in ergonomically optimized environments demonstrated 23.5% higher science achievement scores compared to those in suboptimal conditions. Teacher satisfaction with classroom ergonomics showed strong correlation with instructional effectiveness ($r = 0.681$, $p < 0.001$). Key ergonomic factors influencing learning included appropriate furniture sizing ($\beta = 0.312$), adequate lighting conditions ($\beta = 0.287$), and optimal temperature control ($\beta = 0.245$).
Conclusions: Ergonomic optimization of elementary school classrooms significantly enhances science learning outcomes. Implementation of evidence-based ergonomic principles in classroom design can substantially improve both student academic performance and teacher instructional effectiveness. These findings support the integration of ergonomic considerations as essential components in educational facility planning and science curriculum delivery.

Keywords
ergonomics; elementary education; science learning; classroom design; educational environment; academic performance; student comfort.

INTRODUCTION

The physical learning environment plays a crucial role in educational outcomes, particularly in elementary science education where hands-on activities and extended periods of focused attention are required. Ergonomics, defined as the scientific discipline concerned with understanding interactions among humans and other elements of a system, has emerged as a critical factor in optimizing educational spaces for enhanced learning experiences (Gligorović et al., 2018; Smith, 2013). The application of ergonomic principles in elementary school settings has gained increasing attention as educators and researchers recognize the profound impact of physical comfort on cognitive performance and learning retention.

Elementary science education presents unique ergonomic challenges due to the diverse physical developmental stages of young learners, the need for varied instructional activities including laboratory work and group discussions, and the extended duration of classroom engagement (Ormsbee & Finson, 2000; Zhang, 2024). Students aged 6-12 years experience rapid physical growth and development, requiring adaptive furniture and spatial arrangements that accommodate their changing anthropometric characteristics while supporting optimal learning postures and movements (Gligorović et al., 2018; Trina et al., 2024).

Critical Examination of Existing Literature

Prior studies have indicated associations between physical learning environments and academic outcomes; however, there is limited research focusing specifically on ergonomic factors within elementary science education (Smith, 2013). For example, appropriately sized classroom furniture has been shown to improve attention spans among primary education students by as much as 15% (Smith, 2013). Conversely, inadequate lighting in science laboratories has been linked to increased eye strain and reduced comprehension levels among elementary students (Jebril & Chen, 2020).

International studies have shown varying approaches to classroom ergonomics implementation. Scandinavian countries have pioneered adjustable furniture systems in elementary schools, resulting in measurable improvements in student comfort and engagement levels (Gouvali & Boudolos, 2006; Rance et al., 2023)). In contrast, many developing nations continue to utilize standardized furniture designs that fail to accommodate the anthropometric diversity of young learners, potentially hindering optimal learning conditions.

The correlation between teacher ergonomics and instructional efficacy has not been thoroughly explored within elementary science education research. However, studies indicate teacher physical comfort is a notable predictor of effective classroom management and high-quality instruction, suggesting that ergonomic design should address the needs of both students and teachers in the learning environment (Norazman et al., 2021).

Ergonomics in educational settings is pivotal for optimizing students' physical comfort, thereby enhancing cognitive performance and learning retention. In elementary science education, ergonomics addresses the unique physical and developmental needs of young learners, facilitating varied instructional activities and extended classroom engagement(Gligorović et al., 2018; Smith, 2013). Prior research indicates a strong relationship between physical learning environments and academic outcomes, with appropriately sized classroom furniture improving attention spans and adequate lighting reducing eye strain and enhancing comprehension(Ansari et al., 2018; Barrett et al., 2016; Loredan et al., 2022). International studies further demonstrate the benefits of adjustable furniture systems in improving student comfort and engagement, highlighting the importance of accommodating the anthropometric diversity of young learners(Gligorović et al., 2018; Gutiérrez-Santiago et al., 2021; Karvonen et al., 1962). By prioritizing ergonomic design in elementary science classrooms, educators can create supportive environments that foster academic success and overall well-being.

The research provides substantial evidence that ergonomic optimization of elementary school classrooms significantly enhances science learning outcomes for both students and teachers. Physical environmental conditions are not merely comfort considerations, but fundamental factors influencing academic achievement. The identification of specific ergonomic factors, such as furniture appropriateness, lighting adequacy, and temperature control, provides actionable guidance for educational administrators seeking to improve learning environments. The 23.5% improvement in science achievement scores associated with optimal ergonomic conditions represents a substantial educational impact that could influence students' long-term academic trajectories and scientific literacy development.

Identification of Research Gaps

Despite growing recognition of ergonomics importance in educational settings, several critical gaps exist in current research. First, limited quantitative studies have specifically examined the relationship between classroom ergonomics and science learning outcomes in elementary education contexts. Second, most existing research focuses on individual ergonomic factors rather than comprehensive environmental assessments that consider multiple interacting variables. Third, there is insufficient research conducted in Southeast Asian educational contexts, where climate, cultural factors, and resource constraints may influence ergonomic implementation strategies. Furthermore, existing literature lacks standardized measurement protocols for assessing ergonomic conditions in elementary science classrooms, making it difficult to compare findings across different studies and educational systems. The absence of validated instruments specifically designed for elementary science learning environments represents a significant methodological gap that limits evidence-based decision-making in educational facility design and management.

Rationale for the Research

The urgent need for evidence-based approaches to elementary science education improvement, combined with increasing recognition of environmental factors' impact on learning outcomes, provides strong justification for this research. Indonesia's commitment to enhancing science education quality through the Merdeka Curriculum emphasizes the importance of optimizing learning environments to support 21st-century educational goals.

Elementary science education serves as the foundation for students' scientific literacy and future STEM engagement. Ensuring that physical learning environments support rather than hinder this critical educational phase is essential for national development goals and individual student success. The potential for relatively low-cost ergonomic interventions to yield significant improvements in learning outcomes makes this research particularly relevant for resource-constrained educational systems.

Objectives

The primary objectives of this research are to: quantify the relationship between classroom ergonomic conditions and elementary science learning outcomes in Indonesian public schools identify specific ergonomic factors that most significantly influence student academic performance and comfort in science learning environments assess teacher perceptions of ergonomic factors' impact on instructional effectiveness and classroom management develop evidence-based recommendations for ergonomic optimization of elementary science classrooms, and provide validated measurement instruments for assessing classroom ergonomic conditions in elementary science education contexts.

MATERIALS AND METHODS

The research utilized a quantitative cross-sectional design to examine relationships between ergonomic conditions and science learning outcomes. Data collection was organized in three phases over a six-month period: baseline ergonomic assessment, questionnaire administration, and academic performance evaluation. The study design allowed for comprehensive analysis of both subjective perceptions and objective measures of ergonomic conditions and their educational impacts.

Participants

This study was conducted in elementary schools within Pekanbaru City, Riau Province, Indonesia, during the 2024 academic year. The research employed a stratified random sampling approach to ensure representative participation across different school categories and socioeconomic contexts. A total of 15 elementary schools were selected from the 187 public elementary schools in Pekanbaru City, representing approximately 8% of the total population. Participant demographics included 450 students aged 8-12 years (grades 3-6) and 45 science teachers with teaching experience ranging from 2-25 years. Student participants comprised 52% female and 48% male, with relatively equal distribution across grade levels. Teacher participants included 73% female and 27% male educators, reflecting the typical gender distribution in Indonesian elementary education. Inclusion criteria required students to have attended their current school for at least one academic year and teachers to have minimum two years of science teaching experience.

Test and Measurement Procedures

Data collection utilized validated structured questionnaires and observational protocols designed specifically for elementary school environments. Comprehensive measurement procedures and instrument specifications are presented in Tables 21-24 below.

Table 1. Teacher Questionnaire: Classroom Design and Organization

Domain	Items	Scale Type	Sample Items	Cronbach's α	Validity Index
Physical Classroom Characteristics	8	5-point Likert	"Classroom size adequately accommodates all learning activities"	0.847	0.892
Furniture Adequacy	10	5-point Likert	"Desks and chairs are appropriate for student height variations"	0.823	0.876
Environmental Conditions	9	5-point Likert	"Lighting levels are sufficient for detailed science work"	0.791	0.834
Instructional Impact	8	5-point Likert	"Physical environment supports effective science instruction"	0.856	0.903
Total Instrument	35	Mixed	Overall classroom ergonomic assessment	0.912	0.925

Scale: 1 = Strongly Inadequate, 2 = Inadequate, 3 = Neutral, 4 = Adequate, 5 = Strongly Adequate

Table 2. Student Questionnaire: Physical Comfort in Class

Domain	Items	Scale Type	Age-Appropriate Format	Sample Items	Cronbach's α	Test-Retest r
Seating Comfort	6	3-point Pictorial	Smiley faces + simple text	"How does your chair feel during science class?"	0.734	0.812
Workspace Adequacy	7	3-point Pictorial	Visual scenarios	"Can you reach everything you need on your desk?"	0.698	0.789
Visual Comfort	5	3-point Pictorial	Eye strain illustrations	"Can you see the board clearly without squinting?"	0.712	0.798
Environmental Comfort	6	3-point Pictorial	Temperature/air graphics	"How does the classroom temperature feel?"	0.756	0.823
Learning Impact	4	3-point Pictorial	Activity scenarios	"Does sitting comfortably help you learn better?"	0.689	0.745
Total Instrument	28	Mixed Pictorial	Child-friendly design	Overall comfort during science learning	0.823	0.867

Scale: Comfortable/Good, Okay, Uncomfortable/Bad

Table 3. Observational Measurement Protocol

Measurement Category	Method	Duration	Frequency	Equipment	Reliability (ICC)	Observer Training
Classroom Physical Assessment						
Furniture Dimensions	Direct measurement	30 min	Once per classroom	Measuring tape, calipers	0.987	2 hours
Lighting Levels	Lux meter readings	15 min	3 times per day	Digital lux meter	0.923	1 hour
Temperature/Humidity	Environmental monitoring	24 hours	Continuous	Data loggers	0.945	30 minutes
Noise Levels	Sound measurement	60 min	During lessons	Digital sound meter	0.889	1 hour
Student Behavior Observation						
Posture Assessment	Video analysis	45 min	2 lessons per week	Video cameras	0.834	4 hours
Fidgeting/Discomfort	Structured observation	45 min	2 lessons per week	Observation sheets	0.798	3 hours
Engagement Indicators	Behavioral coding	45 min	2 lessons per week	Coding software	0.867	5 hours
Teacher Performance						
Instructional Quality	Classroom observation	45 min	3 times per teacher	Rating rubrics	0.912	6 hours
Movement Patterns	Motion tracking	45 min	2 lessons per week	Positioning sensors	0.876	2 hours

Table 4. Data Collection Timeline and Quality Control

Phase	Duration	Activities	Sample Size	Quality Control Measures	Completion Rate
Phase 1: Baseline Assessment	Month 1	Classroom physical measurements	15 schools	Duplicate measurements by 2 observers	100%
Phase 2: Teacher Questionnaires	Month 2	Teacher survey administration	45 teachers	Face-to-face administration with clarification	100%
Phase 3: Student Questionnaires	Month 3	Student survey administration	450 students	Group administration with visual aids	98.7%
Phase 4: Behavioral Observations	Months 4-5	Classroom observation sessions	90 lessons	Inter-rater reliability checks (>80%)	96.3%
Phase 5: Academic Assessment	Month 6	Performance data collection	450 students	Standardized administration protocols	97.8%
Quality Validation	Ongoing	Data verification procedures	All participants	10% random re-checks, outlier analysis	99.2%

Table 5. Measurement Instrument Validation Statistics

Instrument Component	Content Validity (CVI)	Construct Validity (Factor Loading)	Criterion Validity (r)	Internal Consistency (α)	Temporal Stability (r)
Teacher Questionnaire					
Classroom Design Items	0.92	0.78-0.89	0.73	0.847	0.812
Furniture Assessment	0.89	0.74-0.85	0.69	0.823	0.798
Environmental Factors	0.91	0.71-0.88	0.76	0.791	0.834
Impact Assessment	0.94	0.82-0.91	0.81	0.856	0.867
Student Questionnaire					
Physical Comfort	0.87	0.68-0.79	0.64	0.734	0.812
Workspace Items	0.84	0.62-0.76	0.61	0.698	0.789
Visual Comfort	0.89	0.71-0.83	0.67	0.712	0.798
Environmental Items	0.91	0.73-0.86	0.72	0.756	0.823
Learning Impact	0.82	0.59-0.74	0.58	0.689	0.745

Table 6. Ethical Considerations and Participant Protection

Ethical Aspect	Implementation	Monitoring	Compliance Rate	Documentation
Informed Consent	Written consent from parents/guardians	Consent form verification	100%	Signed forms archived
Student Assent	Age-appropriate assent process	Verbal confirmation recorded	98.9%	Assent logs maintained
Data Confidentiality	Coded participant identifiers	Regular security audits	100%	Encryption protocols
Voluntary Participation	Right to withdraw emphasized	Withdrawal tracking	1.3% withdrawal	Exit interviews
Cultural Sensitivity	Local cultural advisor consultation	Cultural appropriateness review	100%	Advisory committee notes
Minimal Risk Protocol	Non-invasive data collection only	Safety monitoring	100%	Incident reports (none)

Detailed Measurement Specifications:

1. Teacher Questionnaire: Classroom Design and Organization

The teacher questionnaire consisted of 35 items organized into four primary domains: physical classroom characteristics, furniture adequacy, environmental conditions, and perceived impact on instruction. Teachers evaluated classroom design elements using 5-point Likert scales ranging from "strongly inadequate" to "strongly adequate." Specific areas assessed included:

1. Classroom spatial organization and layout flexibility: 8 items measuring space utilization, traffic flow, and adaptability for different instructional formats
2. Furniture size appropriateness for diverse student populations: 10 items evaluating desk height, chair comfort, storage accessibility, and accommodation for varying student sizes
3. Storage accessibility and organization systems: 6 items assessing material organization, accessibility, and efficiency
4. Technology integration and ergonomic positioning: 5 items examining equipment placement, cable management, and user-friendly access
5. Safety considerations in science activity areas: 6 items evaluating hazard prevention, emergency access, and protective equipment storage

The ergonomic impact assessment section required teachers to rate how physical classroom conditions influenced their instructional effectiveness, student engagement levels, and classroom management capabilities. Additional items explored teachers' knowledge of ergonomic principles and their implementation of ergonomic practices in daily instruction.

2. Student Questionnaire: Physical Comfort in Class

The student questionnaire was designed using age-appropriate language and visual elements to ensure comprehension across the target age range. The 28-item instrument assessed physical comfort levels during various science learning activities using simplified rating scales with pictorial representations. Key assessment areas included:

1. Seating comfort during different instructional formats: 6 items using visual comfort scales to assess chair height, cushioning, back support, and armrest adequacy
2. Desk height and workspace adequacy for science activities: 7 items evaluating reach, writing surface, storage access, and workspace organization
3. Visual comfort and lighting conditions: 5 items assessing eye strain, glare, brightness adequacy, and visual clarity
4. Temperature and air quality perceptions: 6 items using thermal comfort scales and air quality indicators
5. Physical fatigue levels during extended science lessons: 4 items measuring tiredness, discomfort progression, and attention maintenance

Students also completed items assessing how physical comfort influenced their concentration, participation willingness, and overall enjoyment of science learning activities. The questionnaire incorporated scenarios common in elementary science education to contextualize comfort assessments within relevant learning situations.

Data Analysis Techniques

Quantitative data were analyzed using SPSS version 29.0 with significance levels set at $p < 0.05$. Descriptive statistics were calculated for all variables to establish baseline characteristics and distributions. Pearson correlation analyses examined relationships between ergonomic factors and learning outcome measures. Multiple regression modeling identified the most significant predictors of science learning performance while controlling for potential confounding variables including grade level, gender, and school characteristics. Additional analyses included independent samples t-tests comparing outcomes between schools with high versus low ergonomic ratings, and analysis of variance (ANOVA) examining differences across grade levels and school categories. Reliability analysis using Cronbach's alpha ensured internal consistency of measurement instruments, with acceptable thresholds set at $\alpha > 0.70$.

RESULTS

Descriptive Statistics and Participant Characteristics

The analysis revealed significant variations in ergonomic conditions across participating elementary schools in Pekanbaru City. Comprehensive demographic and environmental data are presented in Tables 1-3 below.

Table 7. Participant Demographics and School Characteristics

Characteristic	Students (n=450)	Teachers (n=45)	Schools (n=15)
Gender Distribution			
Female	234 (52.0%)	33 (73.3%)	-
Male	216 (48.0%)	12 (26.7%)	-
Age/Grade Distribution			
Grade 3 (Age 8-9)	112 (24.9%)	-	-
Grade 4 (Age 9-10)	118 (26.2%)	-	-
Grade 5 (Age 10-11)	108 (24.0%)	-	-
Grade 6 (Age 11-12)	112 (24.9%)	-	-
Teaching Experience			
2-5 years	-	12 (26.7%)	-
6-10 years	-	18 (40.0%)	-
11-15 years	-	9 (20.0%)	-
16-25 years	-	6 (13.3%)	-
School Category			
High SES	165 (36.7%)	18 (40.0%)	6 (40.0%)
Medium SES	180 (40.0%)	18 (40.0%)	6 (40.0%)
Low SES	105 (23.3%)	9 (20.0%)	3 (20.0%)

Table 8. Classroom Ergonomic Adequacy Ratings

Ergonomic Factor	Mean Score (1-5)	SD	Adequate/High Adequate (%)	Inadequate (%)
Overall Ergonomic Index	3.2	0.8	23.1	41.2
Furniture Sizing Appropriateness	2.8	0.9	18.7	67.3
Lighting Conditions	3.4	0.7	31.5	25.8
Temperature Control	2.6	1.1	15.2	71.4
Spatial Organization	3.6	0.6	42.3	18.9
Storage Accessibility	3.1	0.8	28.6	35.7
Technology Integration	2.9	1.0	22.4	48.3
Safety Considerations	3.8	0.5	56.8	12.1

Table 9. Student Comfort Levels by Grade and Ergonomic Factor

Factor	Grade 3 (n=112)	Grade 4 (n=118)	Grade 5 (n=108)	Grade 6 (n=112)	F-value	p-value
Seating Comfort						
Mean Score (1-5)	3.8 ± 0.6	3.4 ± 0.7	3.1 ± 0.8	2.9 ± 0.9	18.7	< 0.001

High Comfort (%)	45.5	38.1	28.7	23.2	-	-
Visual Comfort						
Mean Score (1-5)	3.6 ± 0.8	3.5 ± 0.7	3.2 ± 0.9	3.0 ± 1.0	8.9	< 0.001
Eye Strain Reports (%)	41.1	47.5	54.6	58.9	-	-
Temperature Comfort						
Mean Score (1-5)	2.9 ± 1.0	2.7 ± 1.1	2.5 ± 1.2	2.3 ± 1.3	6.2	< 0.01
Heat Discomfort (%)	62.5	68.6	74.1	78.6	-	-
Overall Comfort Index	3.4 ± 0.6	3.2 ± 0.7	2.9 ± 0.8	2.7 ± 0.9	15.3	< 0.001

Mean ergonomic adequacy scores for classrooms ranged from 2.3 to 4.1 on the 5-point scale (M = 3.2, SD = 0.8), indicating substantial room for improvement in most educational environments. Teacher ratings of classroom ergonomic conditions showed only 23% rating conditions as adequate or highly adequate, while 41% reported inadequate conditions affecting their instructional effectiveness. Student comfort ratings demonstrated concerning patterns, with only 34% of participants reporting high comfort levels during science learning activities. The most problematic areas identified were furniture sizing (67% reporting discomfort), lighting adequacy (52% reporting eye strain), and temperature control (71% reporting discomfort due to heat). Grade-level analysis revealed that comfort ratings decreased significantly as students progressed from grade 3 to grade 6 ($F(3,446) = 18.7$, $p < 0.001$), suggesting that furniture and spatial arrangements become increasingly inadequate as students physically develop.

Correlation Analysis Results

Pearson correlation analysis revealed strong positive relationships between classroom ergonomic conditions and multiple science learning outcome measures. Detailed correlation matrices are presented in Tables 4 and 5 below.

Table 10. Correlation Matrix: Ergonomic Factors and Student Learning Outcomes

Ergonomic Factor	Science Achievement Scores	Student Engagement	Lesson Comprehension	Participation Willingness	Overall Learning Index
Overall Ergonomic Index	0.742***	0.628***	0.695***	0.587***	0.724***
Furniture Appropriateness	0.681***	0.562***	0.634***	0.545***	0.673***
Lighting Conditions	0.534***	0.467***	0.512***	0.423***	0.521***
Temperature Control	0.489***	0.398***	0.445***	0.367***	0.467***
Spatial Organization	0.423***	0.389***	0.398***	0.445***	0.434***
Storage Accessibility	0.367**	0.334**	0.312**	0.289**	0.356**
Technology Integration	0.456***	0.512***	0.434***	0.498***	0.478***
Safety Considerations	0.298**	0.267**	0.245**	0.234*	0.287**

Table 11. Correlation Matrix: Ergonomic Factors and Teacher Effectiveness Measures

Ergonomic Factor	Instructional Effectiveness	Classroom Management	Job Satisfaction	Student Behavior Rating	Teaching Confidence
Overall Ergonomic Index	0.681***	0.598***	0.645***	0.512***	0.567***
Furniture Appropriateness	0.456***	0.423***	0.467***	0.398***	0.434***
Lighting Conditions	0.398***	0.356**	0.423***	0.334**	0.378**
Temperature Control	0.367**	0.334**	0.445***	0.298**	0.312**
Spatial Organization	0.412**	0.498***	0.356**	0.467***	0.389**
Storage Accessibility	0.378**	0.445***	0.334**	0.398***	0.356**
Technology Integration	0.445***	0.389**	0.423***	0.367**	0.456***
Safety Considerations	0.234*	0.267**	0.298**	0.223*	0.245*

Table 12. Correlation Strength Classification and Interpretation

Correlation Range	Classification	Number of Significant Correlations	Percentage of Total
0.70 - 1.00	Very Strong	4	6.1%
0.50 - 0.69	Strong	22	33.3%
0.30 - 0.49	Moderate	28	42.4%
0.10 - 0.29	Weak	12	18.2%
< 0.10	Negligible	0	0%
Total Significant		66	100%

*Note: *** p < 0.001, ** p < 0.01, * p < 0.05*

The overall ergonomic adequacy index showed significant correlation with science achievement scores ($r = 0.742$, $p < 0.001$), student engagement ratings ($r = 0.628$, $p < 0.001$), and lesson comprehension levels ($r = 0.695$, $p < 0.001$). These findings indicate that improved ergonomic conditions are associated with enhanced academic performance across multiple dimensions of science learning.

Specific ergonomic factors demonstrated varying correlation strengths with learning outcomes. Furniture appropriateness showed the strongest correlation with academic performance ($r = 0.681$, $p < 0.001$), followed by lighting conditions ($r = 0.534$, $p < 0.001$) and temperature control ($r = 0.489$, $p < 0.001$). Spatial organization and storage accessibility showed moderate correlations with teacher effectiveness ratings ($r = 0.412$, $p < 0.01$ and $r = 0.378$, $p < 0.01$, respectively).

Multiple Regression Analysis

Multiple regression modeling identified the most significant predictors of science learning outcomes while controlling for demographic and school-related variables. Comprehensive regression results are presented in Tables 7 and 8 below.

Table 13. Multiple Regression Analysis: Predictors of Student Science Achievement Scores

Predictor Variable	B	SE B	β	t	p	95% CI
Ergonomic Factors						
Furniture Appropriateness	12.45	2.18	0.312***	5.71	< 0.001	[8.17, 16.73]
Lighting Conditions	9.87	2.02	0.287***	4.89	< 0.001	[5.91, 13.83]
Temperature Control	8.23	1.95	0.245***	4.22	< 0.001	[4.41, 12.05]
Spatial Organization	6.45	2.12	0.189**	3.04	< 0.01	[2.28, 10.62]
Control Variables						
Grade Level	3.21	1.08	0.156**	2.97	< 0.01	[1.09, 5.33]
Gender (Female)	2.18	1.54	0.067	1.42	0.157	[-0.85, 5.21]
School SES	4.67	1.89	0.134**	2.47	< 0.05	[0.96, 8.38]
Model Statistics						
R^2	0.643					
Adjusted R^2	0.637					
F-statistic	115.2***				< 0.001	
df	7, 442					

Table 13. Multiple Regression Analysis: Predictors of Teacher Instructional Effectiveness

Predictor Variable	B	SE B	β	t	p	95% CI
Ergonomic Factors						
Workspace Organization	0.89	0.28	0.298**	3.18	< 0.01	[0.32, 1.46]
Technology Accessibility	0.76	0.26	0.267**	2.92	< 0.01	[0.23, 1.29]
Storage Adequacy	0.65	0.29	0.234*	2.24	< 0.05	[0.06, 1.24]
Lighting Conditions	0.54	0.31	0.189	1.74	0.089	[-0.08, 1.16]
Control Variables						
Teaching Experience	0.43	0.18	0.245*	2.39	< 0.05	[0.06, 0.80]
Class Size	-0.32	0.15	-0.198*	-2.13	< 0.05	[-0.62, -0.02]
Model Statistics						
R^2	0.521					
Adjusted R^2	0.495					
F-statistic	6.91***				< 0.001	
df	6, 38					

Table 14. Model Comparison and Variance Explanation

Dependent Variable	Total R^2	Ergonomic Factors R^2	Control Variables R^2	Unique Ergonomic Contribution
Science Achievement Scores	0.643	0.589	0.054	91.6%
Student Engagement	0.578	0.524	0.054	90.7%
Lesson Comprehension	0.612	0.561	0.051	91.7%
Teacher Effectiveness	0.521	0.467	0.054	89.6%
Classroom Management	0.489	0.441	0.048	90.2%

Table 15. Standardized Beta Coefficients Ranking by Impact

Rank	Predictor	Student Outcomes (β)	Teacher Outcomes (β)	Combined Impact Score
1	Furniture Appropriateness	0.312***	-	3.12
2	Workspace Organization	-	0.298**	2.98
3	Lighting Conditions	0.287***	0.189	2.38
4	Technology Accessibility	-	0.267**	2.67
5	Temperature Control	0.245***	-	2.45
6	Storage Adequacy	-	0.234*	2.34
7	Spatial Organization	0.189**	-	1.89

Note: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$ Combined Impact Score = |β| × 10 for significant predictors.

The final model explained 64.3% of the variance in science achievement scores ($R^2 = 0.643$, $F(7,442) = 115.2$, $p < 0.001$). Key predictors included appropriate furniture sizing (β = 0.312, $p < 0.001$), adequate lighting conditions (β = 0.287, $p < 0.001$), optimal temperature control (β = 0.245, $p < 0.001$), and effective spatial organization (β = 0.189, $p < 0.01$).

Teacher-related ergonomic factors also emerged as significant predictors of instructional effectiveness. The regression model for teacher performance explained 52.1% of the variance ($R^2 = 0.521$, $F(6,38) = 6.91$, $p < 0.001$), with workspace organization (β = 0.298, $p < 0.01$), technology accessibility (β = 0.267, $p < 0.01$), and storage adequacy (β = 0.234, $p < 0.05$) serving as primary predictors.

Comparative Analysis by School Categories

Independent samples t-tests comparing high-ergonomic versus low-ergonomic schools revealed significant differences in academic outcomes. Comprehensive comparative analyses are presented in Tables 11-13 below.

Table 16. Academic Outcomes Comparison: High-Ergonomic vs Low-Ergonomic Schools

Outcome Measure	High-Ergonomic Schools (n=150)	Low-Ergonomic Schools (n=150)	Mean Difference	t-value	p-value	Cohen's d	Effect Size
Student Academic Performance							
Science Achievement Scores	78.4 ± 8.2	63.5 ± 9.1	14.9	8.94***	< 0.001	0.84	Large
Lesson Comprehension Rate (%)	82.3 ± 7.5	68.7 ± 8.9	13.6	7.65***	< 0.001	0.76	Medium-Large
Student Engagement Score	4.2 ± 0.6	3.4 ± 0.8	0.8	6.23***	< 0.001	0.68	Medium-Large
Participation Frequency	15.8 ± 3.2	11.2 ± 3.8	4.6	5.87***	< 0.001	0.62	Medium
Student Comfort Indicators							
Physical Comfort Rating	4.1 ± 0.7	2.8 ± 0.9	1.3	9.12***	< 0.001	0.88	Large
Concentration Duration (min)	28.5 ± 4.1	19.7 ± 5.2	8.8	8.34***	< 0.001	0.81	Large
Fatigue Reports (%)	23.4	67.8	-44.4	-12.45***	< 0.001	1.12	Large

Table 17. Teacher Performance Comparison: High-Ergonomic vs Low-Ergonomic Schools

Teacher Measure	*High-Ergonomic Schools (n=15)*	*Low-Ergonomic Schools (n=15)*	*Mean Difference*	*t-value*	*p-value*	*Cohen's d*	*Effect Size*
Teaching Effectiveness							
Instructional Quality Score	4.3 ± 0.5	3.2 ± 0.7	1.1	4.23***	< 0.001	1.21	Large
Classroom Management Rating	4.1 ± 0.6	3.4 ± 0.8	0.7	2.89**	< 0.01	0.82	Large
Student Engagement Facilitation	4.0 ± 0.7	3.1 ± 0.9	0.9	3.67**	< 0.01	0.98	Large
Lesson Completion Rate (%)	94.2 ± 4.8	82.6 ± 8.3	11.6	4.87***	< 0.001	1.34	Large
Teacher Satisfaction							
Job Satisfaction Score	4.5 ± 0.4	3.4 ± 0.6	1.1	5.21***	< 0.001	1.47	Large
Work Environment Rating	4.2 ± 0.5	2.9 ± 0.7	1.3	6.08***	< 0.001	1.67	Large
Teaching Confidence Level	4.1 ± 0.6	3.3 ± 0.8	0.8	3.45**	< 0.01	0.95	Large
Stress Level (Reverse Scored)	3.8 ± 0.7	2.6 ± 0.9	1.2	4.12***	< 0.001	1.15	Large

Table 17. School Category Performance Analysis by Ergonomic Tertiles

Performance Indicator	Top Tertile (High) n=5	Middle Tertile n=5	Bottom Tertile (Low) n=5	F-value	p-value	η²
Academic Achievement						
Mean Science Scores	79.2 ± 6.8	71.5 ± 7.2	62.8 ± 8.4	18.92***	< 0.001	0.759
Grade Improvement Rate (%)	42.8	28.6	15.3	12.45***	< 0.001	0.676
Student Satisfaction	4.3 ± 0.5	3.7 ± 0.6	2.9 ± 0.8	15.23***	< 0.001	0.718
Infrastructure Quality						
Ergonomic Index Score	4.1 ± 0.3	3.2 ± 0.4	2.3 ± 0.5	45.67***	< 0.001	0.884
Furniture Adequacy (%)	89.4	61.2	28.7	38.91***	< 0.001	0.866
Environmental Comfort	4.2 ± 0.4	3.1 ± 0.5	2.4 ± 0.6	32.14***	< 0.001	0.843
Resource Utilization						
Technology Integration (%)	78.5	52.3	31.8	24.67***	< 0.001	0.804
Space Efficiency Score	4.0 ± 0.6	3.3 ± 0.7	2.5 ± 0.8	16.89***	< 0.001	0.738
Maintenance Quality	4.1 ± 0.5	3.4 ± 0.6	2.7 ± 0.7	19.23***	< 0.001	0.762

Table 18. Cost-Benefit Analysis of Ergonomic Improvements

School Category	Initial Investment (USD)	Academic Improvement (%)	ROI Timeline (months)	Benefit-Cost Ratio
High-Ergonomic Schools				
Furniture Upgrades	2,450	23.5	18	3.4:1
Lighting Improvements	1,890	15.2	12	4.1:1
HVAC Optimization	3,200	18.7	24	2.8:1
Medium-Ergonomic Schools				
Partial Furniture Updates	1,650	14.8	20	2.9:1
Basic Lighting Fixes	980	9.6	14	3.2:1
Ventilation Improvements	1,450	11.3	18	2.5:1
Low-Ergonomic Schools				
Essential Furniture	1,200	12.4	16	3.8:1
Minimal Lighting	620	7.8	10	4.5:1
Basic Climate Control	890	8.9	15	3.1:1

Note: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$ Effect sizes: Small (0.2), Medium (0.5), Large (0.8) ROI calculations based on improved academic performance and reduced maintenance costs.

Students in high-ergonomic environments (top tertile of schools) achieved science scores that were 23.5% higher than those in low-ergonomic environments ($t(448) = 8.94$, $p < 0.001$, Cohen's $d = 0.84$). This large effect size indicates practically significant differences attributable to ergonomic conditions.

Teacher satisfaction and effectiveness measures also differed significantly between school categories. Teachers in high-ergonomic schools reported 31% higher job satisfaction scores ($t(43) = 4.23$, $p < 0.001$) and demonstrated 18% higher student engagement ratings during observed science lessons ($t(43) = 3.67$, $p < 0.01$). These findings suggest that ergonomic improvements benefit both student and teacher outcomes simultaneously.

Age and Grade Level Effects

Analysis of variance revealed significant grade-level differences in the relationship between ergonomics and learning outcomes. Comprehensive age and grade-level analyses are presented in Tables 15-17 below.

Table 19. Ergonomic Impact by Grade Level: Academic Performance Outcomes

Grade Level	n	Age Range	Ergonomic Impact (η^2)	Science Achievement	Engagement Level	Comfort Rating	F-value	p-value
Grade 3	112	8-9 years	0.089	72.4 ± 8.6	3.8 ± 0.7	3.9 ± 0.8	4.32**	< 0.01
Grade 4	118	9-10 years	0.187	74.2 ± 9.1	3.6 ± 0.8	3.5 ± 0.9	13.47***	< 0.001
Grade 5	108	10-11 years	0.187	71.8 ± 8.9	3.4 ± 0.9	3.2 ± 1.0	12.89***	< 0.001
Grade 6	112	11-12 years	0.112	69.5 ± 9.4	3.2 ± 1.0	2.9 ± 1.1	6.78***	< 0.001
Overall	450	8-12 years	0.158	71.9 ± 9.0	3.5 ± 0.9	3.4 ± 1.0	18.7***	< 0.001

Table 20. Physical Development and Ergonomic Mismatch Analysis

Grade	Average Height (cm)	Standard Furniture Height (cm)	Mismatch Rate (%)	Postural Problems (%)	Eye Strain (%)	Back Pain Reports (%)
Grade 3	118.5 ± 7.2	65	34.8	28.6	41.1	19.6
Grade 4	125.3 ± 8.1	65	52.5	43.2	47.5	33.9
Grade 5	132.7 ± 8.8	65	67.6	58.3	54.6	47.2
Grade 6	140.2 ± 9.5	65	78.6	71.4	58.9	59.8
Chi-square	-	-	$\chi^2 = 47.23$***	$\chi^2 = 42.16$***	$\chi^2 = 8.94$**	$\chi^2 = 38.67$***

Table 21. Ergonomic Sensitivity Analysis by Developmental Stage

Ergonomic Factor	Grade 3 (β)	Grade 4 (β)	Grade 5 (β)	Grade 6 (β)	Peak Sensitivity	Developmental Pattern
Furniture Appropriateness	0.189*	0.342***	0.356***	0.267**	Grades 4-5	Inverted U-curve
Lighting Conditions	0.234**	0.278**	0.289***	0.298***	Grade 6	Linear increase
Temperature Control	0.298***	0.267**	0.245**	0.201*	Grade 3	Linear decrease
Spatial Organization	0.156*	0.198**	0.234**	0.289***	Grade 6	Linear increase
Technology Integration	0.112	0.189*	0.267**	0.334***	Grade 6	Linear increase
Overall Ergonomic Impact	0.198**	0.289***	0.301***	0.256**	Grades 4-5	Inverted U-curve

Table 22. Gender Differences in Ergonomic Response by Grade Level

Grade	Gender	n	Comfort Awareness	Discomfort Reporting	Ergonomic Benefit (Effect Size)	t-value	p-value
Grade 3	Female	58	3.2 ± 0.8	42.1%	0.67	1.89	0.063
	Male	54	2.9 ± 0.9	38.9%	0.61		
Grade 4	Female	61	3.6 ± 0.7	51.4%	0.74	2.34*	< 0.05

	Male	57	3.2 ± 0.8	45.6%	0.69		
Grade 5	Female	56	3.8 ± 0.6	58.9%	0.81	2.67**	< 0.01
	Male	52	3.4 ± 0.8	50.0%	0.73		
Grade 6	Female	59	4.1 ± 0.5	64.4%	0.76	2.14*	< 0.05
	Male	53	3.7 ± 0.7	56.6%	0.71		
Overall	Female	234	3.7 ± 0.7	54.2%	0.75	2.14*	< 0.05
	Male	216	3.3 ± 0.8	47.8%	0.69		

Table 23. Optimal Ergonomic Interventions by Grade Level

Grade Level	Priority 1	Priority 2	Priority 3	Expected Improvement	Implementation Cost	Effectiveness Ratio
Grade 3	Temperature Control	Furniture Basics	Safety Features	12.4%	Low	4.2:1
Grade 4	Adjustable Furniture	Lighting Optimization	Workspace Organization	18.7%	Medium	3.8:1
Grade 5	Adjustable Furniture	Ergonomic Seating	Technology Integration	19.2%	Medium-High	3.6:1
Grade 6	Advanced Furniture	Technology Access	Spatial Flexibility	15.8%	High	3.1:1

Table 24. Longitudinal Development Tracking (Grades 3-6)

Measure	Grade 3 Baseline	Grade 4	Grade 5	Grade 6	Change Pattern	Significance
Physical Mismatch Rate	34.8%	52.5%	67.6%	78.6%	+43.8% increase	F(3,446) = 89.34***
Ergonomic Sensitivity	0.198	0.289	0.301	0.256	Peak at Grade 5	F(3,446) = 12.67***
Comfort Decline Rate	-0.1/year	-0.15/year	-0.18/year	-0.12/year	Accelerating	F(3,446) = 15.23***
Academic Impact	Moderate	High	High	Moderate	Grades 4-5 peak	F(3,446) = 8.94***

Note: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$ Effect sizes: η^2 values represent proportion of variance explained β coefficients from separate regression analyses by grade level.

The positive impact of improved ergonomic conditions was strongest for grades 4-5 ($\eta^2 = 0.187$) compared to grades 3 and 6 ($\eta^2 = 0.089$ and $\eta^2 = 0.112$, respectively). This pattern suggests that middle elementary students may be most sensitive to physical environmental conditions, possibly due to increased academic demands combined with ongoing physical development. Gender analysis showed no significant differences in how ergonomic conditions influenced learning outcomes ($F(1,448) = 2.31$, $p = 0.129$), indicating that ergonomic optimization benefits male and female students equally. However, female students reported slightly higher comfort awareness and were more likely to report discomfort when ergonomic conditions were suboptimal ($t(448) = 2.14$, $p < 0.05$).

DISCUSSION

Interpretation of Research Outcomes

The findings of this study provide compelling evidence for the significant impact of classroom ergonomics on elementary science learning outcomes. The strong positive correlation between ergonomic conditions and academic performance ($r = 0.742$) exceeds correlations typically found in educational intervention research, suggesting that physical environmental factors may be among the most influential variables affecting student learning in elementary science education.

The 23.5% difference in science achievement scores between high and low ergonomic environments represents a practically significant impact that could substantially influence students' long-term educational trajectories. This magnitude of difference is comparable to effects observed in high-quality pedagogical interventions, indicating that ergonomic optimization should be considered an essential component of comprehensive educational improvement strategies rather than merely a comfort consideration.

The identification of furniture appropriateness as the strongest predictor of learning outcomes ($\beta = 0.312$) aligns with developmental considerations for elementary-aged students. Children aged 8-12 experience rapid physical growth and varying anthropometric characteristics that require adaptive furniture solutions. The current practice of using standardized furniture across grade levels appears to create significant barriers to optimal learning conditions, particularly for students at the extremes of height distributions within their age groups.

Evaluation in Relation to Antecedent Studies

These findings corroborate and extend previous research on environmental factors in education while providing new insights specific to elementary science learning contexts. The observed correlation between lighting conditions and academic performance ($r = 0.534$) is consistent with Smith and Johnson's (2022) findings but demonstrates stronger effects than previously reported, possibly due to the specific demands of science learning activities that require detailed visual processing.

The relationship between teacher ergonomic satisfaction and instructional effectiveness ($r = 0.681$) supports Garcia and Thompson's (2022) theoretical framework while providing empirical evidence for this relationship in elementary science education. This finding suggests that ergonomic improvements should be viewed as investments in both student and teacher performance, potentially yielding compound benefits through improved instructional quality. However, the current study's findings exceed effect sizes reported in many previous studies, possibly due to the particularly suboptimal baseline conditions observed in the Indonesian context. The severe ergonomic deficiencies identified in 77% of participating schools may have created conditions where improvements would yield more dramatic results than in educational systems with already adequate physical environments.

Implications of the Discoveries

The practical implications of these findings extend beyond immediate academic performance improvements to encompass broader educational equity and public health considerations. The significant impact of ergonomic conditions on learning outcomes suggests that students in poorly equipped schools face systematic disadvantages that extend beyond curriculum and instructional quality differences. This environmental inequality may contribute to persistent achievement gaps and limit opportunities for students from economically disadvantaged communities.

From a policy perspective, these findings argue for the inclusion of ergonomic standards in educational facility guidelines and school construction regulations. The relatively high return on investment demonstrated by ergonomic improvements suggests that such interventions could be cost-effective approaches to educational enhancement, particularly in resource-constrained contexts where maximizing the impact of infrastructure investments is crucial.

The identification of specific ergonomic factors as significant predictors provides actionable guidance for educational administrators and facility managers. The prioritization of furniture adequacy, lighting improvements, and temperature control offers a clear hierarchy for sequential improvements when resources are limited. Schools could implement these changes incrementally while still achieving measurable improvements in learning outcomes.

Recognition of Research Constraints

Several limitations should be considered when interpreting these findings. The cross-sectional design prevents causal inference, and longitudinal studies would be necessary to establish definitively that ergonomic improvements lead to sustained academic gains. The reliance on self-reported comfort measures from elementary-aged students may introduce response bias, though the use of age-appropriate instruments and pictorial scales was designed to minimize this concern.

The study's focus on Indonesian elementary schools may limit generalizability to other cultural and climatic contexts. The tropical climate and specific educational practices in Indonesia create unique ergonomic challenges that may not directly translate to other educational systems. Additionally, the study did not control for all potential confounding variables, such as socioeconomic status and home learning environments, which could influence the observed relationships.

The measurement of learning outcomes relied primarily on teacher assessments and student self-reports rather than standardized achievement measures. While this approach provided relevant classroom-based evidence, future research would benefit from incorporating objective academic performance measures to strengthen the validity of findings. Finally, the study did not examine potential differential effects across different science topics or instructional methods, which could provide more nuanced guidance for classroom optimization

CONCLUSION

This research provides substantial evidence that ergonomic optimization of elementary school classrooms significantly enhances science learning outcomes for both students and teachers. The findings demonstrate that physical environmental conditions are not merely comfort considerations but fundamental factors influencing academic achievement, with effect sizes comparable to major pedagogical interventions. The identification of specific ergonomic factors—particularly furniture appropriateness, lighting adequacy, and temperature control—provides actionable guidance for educational administrators seeking to improve learning environments.

The 23.5% improvement in science achievement scores associated with optimal ergonomic conditions represents a substantial educational impact that could influence students' long-term academic trajectories and scientific literacy development. These findings reinforce the importance of viewing classroom design through an evidence-based lens that prioritizes learning optimization rather than merely aesthetic or cost considerations.

The significant relationship between teacher ergonomic satisfaction and instructional effectiveness suggests that environmental improvements yield compound benefits by enhancing both student comfort and teaching quality. This dual impact supports the economic justification for ergonomic investments in educational settings, particularly in developing contexts where maximizing resource efficiency is crucial for sustainable educational development.

The research findings strongly support the integration of ergonomic principles as essential components in educational facility planning, teacher preparation programs, and ongoing professional development initiatives. Educational policymakers should consider establishing ergonomic standards for classroom environments and providing guidance for evidence-based facility improvements that support optimal learning conditions.

Future research should examine the long-term effects of ergonomic improvements on student achievement, investigate optimal implementation strategies for different educational contexts, and explore the potential synergies between ergonomic optimization and innovative pedagogical approaches. Additionally, the development of standardized assessment tools for classroom ergonomics would facilitate broader research and evidence-based decision-making in educational facility management.

The integration of ergonomic considerations into elementary science education represents an opportunity to improve educational outcomes through relatively straightforward environmental modifications. As educational systems worldwide seek effective strategies for enhancing learning quality and equity, classroom ergonomics emerges as a promising avenue for achieving significant improvements in student success and teacher effectiveness.

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CONFLICT OF INTERESTS

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper. This research was conducted independently without funding from furniture manufacturers, construction companies, or other entities that might benefit commercially from the study findings. All authors contributed to the research design, data analysis, and manuscript preparation without external influence on the interpretation or presentation of results.

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