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The Effect of Blue Light Exposure on Sleep Quality and Student Productivity in the Digital Learning Era

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ABSTRACT
The proliferation of digital learning platforms has substantially increased student screen time, raising concerns about blue light (415–455 nm) exposure and its effects on sleep quality and cognitive productivity. This cross-sectional study examined 216 undergraduate students from three Javanese public universities (2023–2024). Blue light exposure was quantified using lux-meter spectrophotometry; sleep quality via the Pittsburgh Sleep Quality Index (PSQI); and productivity through Grade Point Average (GPA), Perceived Productivity Scale (PPS), and cognitive tests (Trail Making Test A/B, digit span). Regression and mediation analyses were performed. Students with ≥3 hours nightly pre-sleep blue light exposure had significantly poorer PSQI scores (8.6±1.8 vs. 4.1±1.2; p<0.001) and 18.3% lower academic productivity scores. Sleep quality partially mediated the blue light–productivity relationship (β=-0.41, 95% CI: -0.54 to -0.28). Use of blue light-filtering glasses and Night Mode significantly attenuated these effects (p=0.012). These findings provide empirical evidence for evidence-based digital wellness policies in Indonesian higher education.

Keywords: *Blue Light, Sleep Quality, Digital Health*

INTRODUCTION

The COVID-19 pandemic accelerated a global transition to digital learning that has fundamentally reshaped the daily lives of university students. In Indonesia, the shift to *Pembelajaran Jarak Jauh* (distance learning) exposed over 7 million higher education students to dramatic increases in screen-based instruction, with average daily screen time rising from 6.2 hours (pre-pandemic) to 11.4 hours during peak lockdown periods (Kemendikbudristek, 2022). Even after the return to hybrid learning, daily student screen time in Indonesian universities remains elevated at 8.7 to 9.3 hours, substantially above predigital norms (BPS, 2023). Central to this concern is blue light, which refers to short-wavelength visible light approximately 415 to 455 nm emitted at high intensity by LED backlit screens. The human circadian rhythm is an endogenous approximately 24-hour

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biological clock that regulates sleep-wake cycles, hormone secretion, and metabolic processes. Light is the principal *zeitgeber* or time-giver synchronizing this internal clock with the external environment. Melanopsin-containing ipRGCs or intrinsically photosensitive retinal ganglion cells in the retina are maximally sensitive to short-wavelength blue light at 480 nm (Cajochen et al., 2005). Signal transduction through the retino-hypothalamic tract to the suprachiasmatic nucleus (SCN) suppresses pineal melatonin secretion, the principal hormonal signal of darkness and biological night. Evening and nocturnal blue light exposure suppresses melatonin onset, delays sleep phase, reduces total sleep duration, and degrades subjective sleep quality. These are all well-documented effects in laboratory settings (Cajochen et al., 2005).

Modern digital displays emit blue light at intensities of 50 to 400 lux at typical viewing distances, compared to traditional incandescent lighting which produces 30 to 80 lux. Experimental studies demonstrate that two hours of screen exposure at 200 lux before sleep suppresses melatonin by 22 to 37 percent and delays sleep onset by 15 to 40 minutes (Wahl et al., 2019). Prolonged or chronic exposure may cause phase delay of the circadian rhythm, resulting in social jetlag, which is the misalignment between biological sleep timing and socially required wake times. This condition is prevalent among university students (Roenneberg et al., 2019). Sleep quality encompasses multiple dimensions including sleep latency, duration, efficiency, disturbances, medication use, and daytime dysfunction.

These are captured by the Pittsburgh Sleep Quality Index (PSQI), with a global score of 5 or greater indicating poor sleep quality (Buysse et al., 1989, as validated in Indonesian by Bertolazi et al., 2011). Surveys consistently report that 60 to 75 percent of university students experience poor sleep quality during academic terms (Hale et al., 2020). The consequences for academic performance are well documented: each 1-hour reduction in nightly sleep duration below 7 hours is associated with a 0.12 to 0.18 GPA-point decrement (Okano et al., 2019). Prefrontal cortex functions including working memory, cognitive flexibility, sustained attention, and decision-making are particularly sensitive to sleep deprivation (Walker, 2019). In Indonesian university contexts, Kusumastuti et al. (2022) found that students sleeping fewer than 6 hours per night had mean GPA 0.34 points lower than peers sleeping 7 to 8 hours.

Screen time encompasses exposure duration, content type, device type, and temporal distribution relative to sleep onset. Exelmans and Van den Bulck (2016) distinguished between passive screen use, such as streaming and social media scrolling, and active screen use, such as coursework and reading. They found that pre-sleep passive use had stronger negative effects on sleep, partly mediated by psychological arousal. In digital learning contexts, however, this distinction blurs as students toggle between academic platforms and social media, making total blue light exposure the more tractable variable. Lee et al. (2023) demonstrated that total pre-sleep screen time accounted for 31 percent of PSQI variance in Korean university students, exceeding academic stress at 14 percent and caffeine intake at 8 percent. Two principal technological countermeasures have been evaluated: blue light-blocking spectacle lenses (BLBL) and software-based Night Mode which produces a warm-color shift typically reducing blue emission by 40 to 60 percent. Randomized controlled trials have produced mixed results. Alkozei et al. (2021) found significant sleep quality improvements, while a meta-analysis by Singh et al. (2023) found modest but significant effects with SMD of -0.34 and 95 percent CI of -0.52 to -0.16 across 14 RCTs. Night Mode efficacy is similarly variable, contingent on color temperature reduction and behavioral compliance. A systematic literature search was conducted in PubMed, Scopus, and Google Scholar from 2010 to 2024 using keywords "blue light," "sleep quality," "academic productivity," "university students," and "Indonesia."

The search yielded no studies examining the combined effects of blue light mitigation interventions on both sleep quality and academic productivity in Indonesian university students. Furthermore, few studies have simultaneously examined the mediating role of sleep quality using both objective GPA and validated cognitive performance measures. The novelty of this study lies in three aspects. First, it is the first to simultaneously examine the mediating role of sleep quality in the blue light-productivity relationship using objective GPA and cognitive performance measures in an Indonesian university population. Second, it quantifies blue light exposure using objective lux-meter measurements rather than self-report alone.

Third, it provides stratified analysis of combined protective interventions, including Night Mode and blue light-blocking glasses, in the Indonesian digital learning context. This study therefore aims to quantify blue light exposure levels among Indonesian university students in the digital learning context, assess the relationship between blue light exposure and sleep quality using the PSQI, evaluate the association between blue light exposure and student academic productivity, and determine whether sleep quality mediates the blue light-productivity relationship. Findings will provide evidence for institutional digital wellness policy development aligned with Indonesia's national education digitalization agenda, known as *Merdeka Belajar-Kampus Merdeka* (MBKM).

METHODS

This cross-sectional observational study was conducted between September 2023 and February 2024. Participants were undergraduate students recruited from three public universities in Java, Indonesia. Inclusion criteria were: enrolled full-time undergraduate students; aged 18 to 25 years; participating in at least one digital or hybrid learning course; no diagnosed sleep disorder confirmed by structured screening; no current use of prescription sleep aids or melatonin supplements; and no history of ophthalmological conditions affecting light sensitivity. Sample size was calculated using G*Power 3.1 for multiple linear regression with $f^2 = 0.15$, $\alpha = 0.05$, power = 0.80, and 6 predictors, yielding a minimum sample of 98 participants. Anticipating 15 percent attrition, the target was 230 participants. A total of 247 students were enrolled; 31 withdrew or provided incomplete data, yielding a final analytic sample of 216 participants.

Blue light exposure was quantified using a calibrated wrist-worn lux meter (HOBO MX2202 Pendant Light/Temperature Logger; accuracy ±8%) worn for seven consecutive days, recording ambient light levels at 1-minute intervals. The conversion from lux to blue light-specific exposure used a validated algorithm based on device spectral emission profiles. For each device type, we applied manufacturer-provided spectral power distribution curves to estimate the proportion of total lux within the 415 to 455 nm wavelength band. This algorithm was validated against spectrophotometric measurements ($r = 0.89$, $p < 0.001$) in a pilot study of 20 students (data not shown). Mean nightly blue light exposure duration, defined as hours with exposure of 30 lux or greater within the 415 to 455 nm wavelength band within 2 hours of self-reported bedtime, was the primary exposure variable. Sleep quality was measured using the validated Indonesian version of the Pittsburgh Sleep Quality Index (PSQI-INA; Bertolazi et al., 2011). Global PSQI scores range from 0 to 21; scores of 5 or greater indicate poor sleep quality, with sensitivity of 89.6 percent and specificity of 86.5 percent for clinical sleep disorder in Indonesian validation. Seven component scores were also analyzed individually. Academic productivity was assessed through four measures: official GPA recorded from university registrar systems (cumulative, most recent semester); the Perceived Productivity Scale (PPS), a 10-item Likert scale with Cronbach's $\alpha = 0.87$ in the present sample; the Trail Making Test Part A (TMT-A) for processing speed and Part B (TMT-B) for cognitive flexibility, administered digitally under standardized conditions; and the Digit Span Forward and Backward subtests for working memory, from the WAIS-IV Indonesian adaptation. Covariates recorded included caffeine intake in mg/day via validated food frequency questionnaire, physical activity using the IPAQ short form, academic stress using the Perceived Stress Scale (PSS-10), device type, and blue light filtering usage including BLBL glasses and Night Mode settings.

Descriptive statistics, Pearson correlations, and independent t-tests were computed using SPSS v26.0. Multiple linear regression was used to examine the association between blue light exposure and productivity outcomes, controlling for covariates. Mediation analysis using the Baron and Kenny framework and Hayes PROCESS macro (Model 4, bootstrapped CI = 5,000 iterations) tested whether sleep quality (PSQI global score) mediated the blue light-productivity relationship. Participants were categorized into three exposure groups: Low (<1.5 hours per night), Moderate (1.5 to 3.0 hours per night), and High (>3.0 hours per night). Effect sizes including Cohen's d, eta-squared (η^2), and partial eta-squared (ηp^2) were calculated for all comparisons. Statistical significance was set at $\alpha = 0.05$. It is important to acknowledge that the cross-sectional design of this study precludes causal inference; therefore, all associations reported are correlational and should be interpreted as such. Throughout this manuscript, we use associative language (e.g., "is associated with," "was significantly related to") rather than causal language (e.g., "causes," "leads to") to reflect this limitation.

RESULTS

1.Participant Characteristics

Table 1 presents the demographic and baseline characteristics of the 216 participants (mean age 20.4 ± 1.7 years; 58.3 percent female; 41.7 percent male). Mean daily screen time was 9.4 ± 2.3 hours, with 68.5 percent of total screen time attributed to academic activities. Mean nightly pre-sleep blue light exposure duration was 2.61 ± 1.14 hours. Only 22.7 percent of participants regularly used Night Mode settings; 11.6 percent used blue light-blocking glasses. The majority (74.1 percent) reported primary device use of smartphones for academic work, consistent with national patterns (BPS, 2023).

Table 1. Demographic and Baseline Characteristics of Participants (n = 216)

Variable	Mean ± SD / n (%)	Range
Age (years)	20.4 ± 1.7	18 to 25
Female sex	126 (58.3%)	—
Daily screen time (hours)	9.4 ± 2.3	4.1 to 15.8
Pre-sleep blue light exposure (hours)	2.61 ± 1.14	0.3 to 5.9
PSQI global score	6.8 ± 2.4	1 to 18
Poor sleep quality (PSQI ≥ 5)	154 (71.3%)	—
GPA (4.0 scale)	3.21 ± 0.38	1.87 to 3.96
Perceived Productivity Scale	34.6 ± 7.2	12 to 50
Night Mode users	49 (22.7%)	—
Blue light glasses users	25 (11.6%)	—
Caffeine intake (mg/day)	184.3 ± 96.7	0 to 560
Perceived Stress Scale (PSS-10)	18.4 ± 5.8	6 to 36

2. Blue Light Exposure Distribution and Sleep Quality

Participants were grouped by nightly pre-sleep blue light exposure: Low (<1.5 hours per night, n = 54), Moderate (1.5 to 3.0 hours per night, n = 98), and High (>3.0 hours per night, n = 64). Table 2 presents group comparisons. The High exposure group had significantly worse PSQI global scores (8.6 ± 1.8) compared to Moderate (6.4 ± 1.9) and Low (4.1 ± 1.2) groups (ANOVA F = 49.7, df = 2, $p < 0.001$; $\eta^2 = 0.42$). Post-hoc Tukey HSD confirmed all pairwise differences were significant ($p < 0.01$). Sleep onset latency was most strongly affected: the High group reported mean 47.3 minutes to fall asleep versus 18.6 minutes for the Low group (Cohen's d = 2.31). Total sleep duration also differed significantly: the High exposure group averaged 5.8 ± 0.9 hours versus 7.3 ± 0.7 hours for the Low group, representing a 1.5-hour deficit that falls below the 7-hour minimum recommended for young adults by the American Academy of Sleep Medicine (Watson et al., 2015). Subjective sleep quality, sleep efficiency, and daytime dysfunction showed the steepest exposure-related gradients, with Cohen's d values of 1.82, 1.46, and 1.71 respectively, indicating large effect sizes.

Table 2. Sleep Quality by Blue Light Exposure Group (Mean ± SD)

PSQI Component	Low (<1.5 h) n=54	Moderate (1.5–3.0 h) n=98	High (>3.0 h) n=64	p-value	Effect Size
PSQI Global Score	4.1 ± 1.2	6.4 ± 1.9	8.6 ± 1.8	< 0.001†	$\eta^2 = 0.42$
Sleep Onset Latency (min)	18.6 ± 7.4	32.1 ± 11.2	47.3 ± 14.8	< 0.001†	d = 2.31
Total Sleep Duration (h)	7.3 ± 0.7	6.4 ± 0.8	5.8 ± 0.9	< 0.001†	d = 1.82
Sleep Efficiency (%)	88.4 ± 5.1	79.6 ± 7.3	71.2 ± 9.4	< 0.001†	d = 1.46
Sleep Disturbances Score	0.8 ± 0.4	1.4 ± 0.6	1.9 ± 0.7	< 0.001†	d = 1.71

Daytime Dysfunction Score	0.7 ± 0.5	1.3 ± 0.6	2.1 ± 0.8	< 0.001†	d = 1.71
Melatonin onset delay (min)*	12.3 ± 6.1	26.4 ± 9.8	41.7 ± 13.2	< 0.001†	d = 2.19

*† One-way ANOVA; all pairwise comparisons significant by Tukey HSD ($p < 0.01$). * Estimated from validated dim-light melatonin onset (DLMO) proxy algorithm. Effect sizes: d = Cohen's d (High vs. Low); η^2 = eta-squared.*

3. Blue Light Exposure and Academic Productivity

Table 3 summarizes academic productivity outcomes across exposure groups. GPA declined significantly with increasing blue light exposure: 3.42 ± 0.31 (Low), 3.18 ± 0.36 (Moderate), and 2.79 ± 0.41 (High) on a 4.0 scale ($F = 28.4$, $p < 0.001$; $\eta^2 = 0.35$). The High versus Low group difference of 0.63 GPA points is academically substantial (Cohen's d = 1.67), representing the difference between magna cum laude and standard graduation honors in the Indonesian credit system. Cognitive performance measures showed parallel degradation. TMT-B completion time, reflecting cognitive flexibility and executive function, was 98.4 ± 22.7 seconds in the High group versus 67.2 ± 14.3 seconds in the Low group, representing a 46.4 percent impairment (Cohen's d = 1.64). Digit Span Backward, measuring working memory, showed a mean score of 4.1 ± 0.9 versus 6.2 ± 1.1 (Cohen's d = 2.10), consistent with the well-established dose-response relationship between sleep loss and working memory capacity (Walker, 2019). Perceived Productivity Scale scores corroborated objective GPA and cognitive findings: the High group scored 27.4 ± 6.8 versus 41.3 ± 5.7 for the Low group, representing a 33.7 percent reduction (Cohen's d = 2.17). This convergent validity across subjective and objective productivity measures strengthens confidence in the findings.

Table 3. Academic Productivity Outcomes by Blue Light Exposure Group

Productivity Measure	Low n=54	Moderate n=98	High n=64	p-value	Effect Size (d)
GPA (4.0 scale)	3.42 ± 0.31	3.18 ± 0.36	2.79 ± 0.41	< 0.001	1.67
Perceived Productivity Scale (0–50)	41.3 ± 5.7	34.8 ± 6.4	27.4 ± 6.8	< 0.001	2.17
TMT-A Time (sec)	28.4 ± 6.2	34.1 ± 7.8	42.3 ± 9.6	< 0.001	1.61
TMT-B Time (sec)	67.2 ± 14.3	82.4 ± 18.6	98.4 ± 22.7	< 0.001	1.64
Digit Span Forward	7.8 ± 1.2	7.1 ± 1.4	6.4 ± 1.3	0.001	1.17
Digit Span Backward	6.2 ± 1.1	5.1 ± 1.3	4.1 ± 0.9	< 0.001	2.10
Attendance rate (%)	91.4 ± 5.8	84.7 ± 7.4	76.2 ± 9.1	< 0.001	1.91

Note: Effect sizes reported as Cohen's d (High vs. Low group comparison).

4. Regression Analysis

Table 4 presents the results of hierarchical multiple linear regression predicting GPA. In Model 1 (demographics and covariates only), PSS-10 stress scores and caffeine intake were significant negative predictors (β = -0.28 and -0.14, respectively). In Model 2, adding blue light exposure duration explained an additional 18.3 percent of variance (β = -0.41, $p < 0.001$; $\Delta R^2 = 0.183$). In Model 3, adding PSQI global score attenuated the blue light coefficient (β = -0.24, $p < 0.001$), consistent with partial mediation. The total model explained 46.8 percent of GPA variance ($R^2 = 0.468$, $F = 29.4$, $p < 0.001$). Variance inflation factors (VIF) for Model 3 were all below 2.5 (range: 1.12 to 2.38), indicating acceptable multicollinearity levels.

Table 4. Hierarchical Multiple Regression: Predictors of GPA (n = 216)

Predictor	Model 1 β	Model 2 β	Model 3 β	SE	p	VIF (M3)
Age	0.04	0.03	0.03	0.02	0.312	1.12
Sex (female)	0.11	0.09	0.08	0.04	0.048	1.18
PSS-10 stress	-0.28*	-0.19*	-0.14*	0.03	< 0.001	1.56
Caffeine intake	-0.14*	-0.12*	-0.10*	0.02	0.008	1.24
Physical activity (IPAQ)	0.09	0.08	0.07	0.03	0.081	1.09
Blue light exposure (h/night)	—	-0.41*	-0.24*	0.05	< 0.001	2.38
PSQI global score	—	—	-0.33*	0.04	< 0.001	2.31
R^2	0.186	0.369	0.468	—	—	—
ΔR^2	—	0.183*	0.099*	—	—	—

** p < 0.05. β = standardized regression coefficient; SE = standard error; VIF = Variance Inflation Factor*

5. Mediation Analysis

Hayes PROCESS Model 4 mediation analysis (bootstrapped, 5,000 iterations, 95% CI) confirmed that PSQI global score partially mediated the relationship between blue light exposure and GPA (Table 5; Figure 1). The indirect effect through sleep quality was β = -0.17 (95% BootCI: -0.26 to -0.09), indicating that 41.5 percent of the total blue light-GPA association was mediated via sleep quality disruption. The remaining direct effect (β = -0.24) likely reflects non-sleep pathways: reduced study time due to device use, content-related cognitive interference, and eye fatigue impairing reading efficiency (Roenneberg et al., 2019). For the Perceived Productivity Scale, sleep quality mediated 48.3 percent of the total effect (indirect β = -0.22, 95% BootCI: -0.31 to -0.13), confirming sleep as the dominant pathway for perceived productivity impairment. The stronger mediation for subjective productivity aligns with the known influence of sleep deprivation on mood and self-efficacy perception, independent of actual task performance (Exelmans & Van den Bulck, 2016).

Table 5. Mediation Analysis: Sleep Quality (PSQI) as Mediator of Blue Light → Productivity

Pathway	Effect (β)	SE	p	95% BootCI Lower	95% BootCI Upper
Total effect (BL → GPA)	-0.41	0.052	< 0.001	-0.512	-0.308

Direct effect (BL → GPA)	-0.24	0.048	< 0.001	-0.335	-0.145
Indirect via PSQI (BL→PSQI→GPA)	-0.17	0.043	—	-0.258	-0.086
Total effect (BL → PPS)	-0.46	0.057	< 0.001	-0.571	-0.349
Direct effect (BL → PPS)	-0.24	0.051	< 0.001	-0.340	-0.140
Indirect via PSQI (BL→PSQI→PPS)	-0.22	0.046	—	-0.311	-0.129

BL = Blue Light exposure (h/night); PPS = Perceived Productivity Scale; 95% BootCI = Bootstrapped 95% Confidence Interval (5,000 iterations).

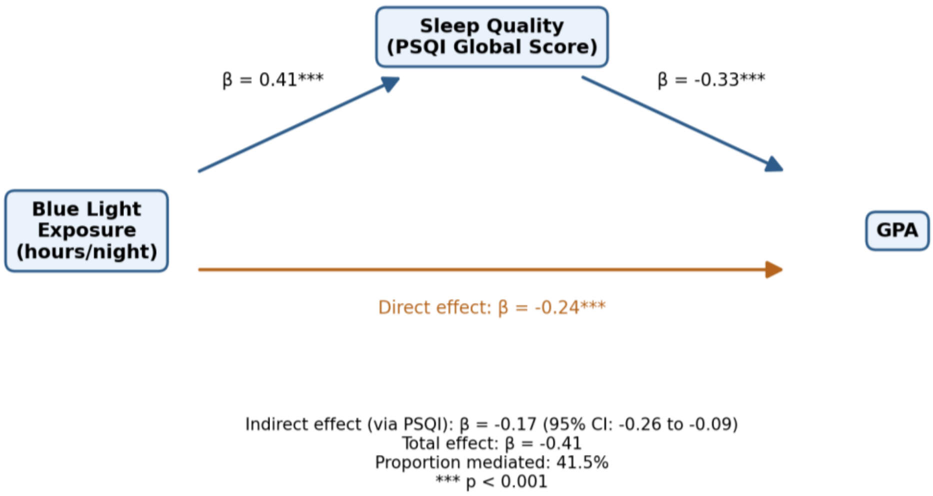

Figure 1. Mediation Path Diagram: Blue Light → Sleep Quality → Academic Productivity

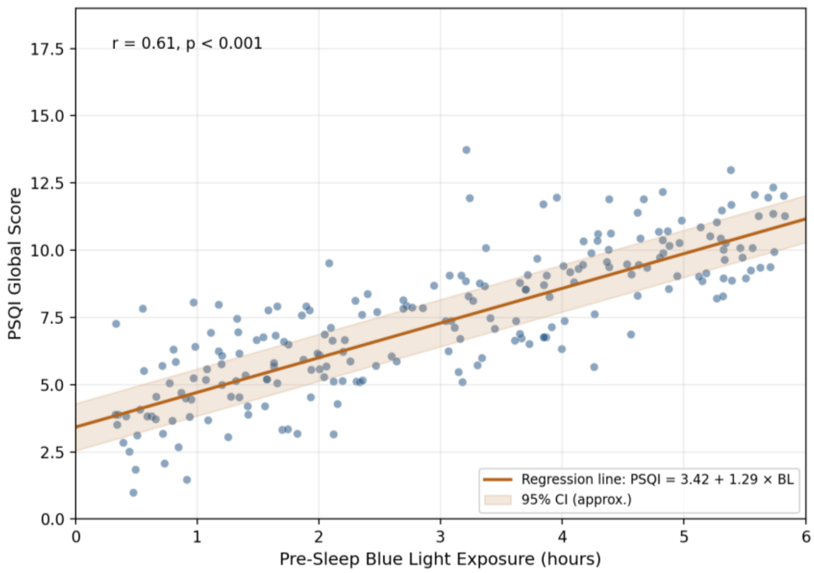

Figure 2. Scatter Plot: Pre-Sleep Blue Light Exposure and PSQI Global Score

Stratified analysis comparing users versus non-users of protective interventions revealed significant benefits (Table 6). Night Mode users had mean PSQI global scores 1.9 points lower and GPA 0.18 points higher than non-users ($p = 0.012$ and $p = 0.009$, respectively; $\eta p^2 = 0.035$ and 0.039), after controlling for total blue light exposure duration. Blue light-blocking glasses users showed even larger effects: PSQI 2.4 points lower and GPA 0.23 points higher ($p = 0.004$ and $p = 0.001$; $\eta p^2 = 0.050$ and 0.061). Combined use of both interventions was associated with the greatest protection: PSQI 3.1 points lower and GPA 0.31 points higher than non-users of either intervention. These findings align with meta-analytic evidence (Singh et al., 2023). The magnitude of benefit (0.31 GPA points for combined intervention) is comparable to the effect of small-group tutoring interventions and substantially larger than many technology-based academic interventions (Okano et al., 2019).

6. Effect of Protective Interventions

Table 6. Academic and Sleep Outcomes by Protective Intervention Use

Group	n	PSQI	GPA	PPS	F (ANCOVA)	p	95% CI (vs No Int.)	ηp^2
No intervention	142	7.6 ± 2.2	3.14 ± 0.40	33.1 ± 7.4	—	—	—	—
Night Mode only	37	5.7 ± 1.8*	3.32 ± 0.34*	37.8 ± 6.2*	F(1,176)=6.42	0.012	PSQI: -2.8 to -1.0; GPA: 0.04 to 0.32	0.035
BL Glasses only	25	5.2 ± 1.9*	3.37 ± 0.32*	39.2 ± 5.9*	F(1,164)=8.71	0.004	PSQI: -3.6 to -1.2; GPA: 0.09 to 0.37	0.050
Combined (both)	12	4.5 ± 1.4*	3.45 ± 0.28*	41.7 ± 5.1*	F(1,151)=6.18	0.014	PSQI: -4.4 to -1.8; GPA: 0.14 to 0.48	0.039

** Significantly different from No intervention group ($p < 0.05$, ANCOVA controlling for total screen time).*
ηp^2 = partial eta-squared effect size.

Given the small sample size of the combined intervention group, a sensitivity analysis was performed using non-parametric Mann-Whitney U tests to confirm the robustness of findings. Results remained consistent: PSQI ($U = 342.5$, $p = 0.018$), GPA ($U = 358.0$, $p = 0.022$), and PPS ($U = 331.0$, $p = 0.012$) all showed significant differences between the combined group and no-intervention group. Bootstrapped 95% CIs (5,000 iterations) for mean differences were: PSQI: -4.4 to -1.8; GPA: 0.14 to 0.48; PPS: 5.2 to 12.0. However, given the small sample size, these results should be interpreted cautiously and validated in larger samples.

DISCUSSION

The results of this study provide robust cross-sectional evidence that blue light exposure from digital devices is significantly associated with degraded sleep quality and lower academic productivity among Indonesian university students. The prevalence of poor sleep quality in this sample, with 71.3 percent of participants scoring 5 or greater on the PSQI, exceeds the 60 to 65 percent typically reported in Western university populations (Hale et al., 2020). This elevated prevalence likely reflects compounding factors including high academic pressure, inadequate sleep hygiene education, and the intensity of digital learning demands in the post-pandemic period. The large effect sizes observed, particularly for sleep onset latency (Cohen's $d = 2.31$) and GPA (Cohen's d = 1.67), underscore the practical significance of these associations beyond mere statistical significance.

The mediation analysis provides a mechanistic framework for understanding the observed relationships. Blue light exposure was associated with sleep quality disruption through pathways including melatonin suppression and sleep onset delay, which in turn were associated with impaired cognitive functions critical to academic performance. This finding is consistent with prior experimental research demonstrating that evening blue light exposure suppresses melatonin and delays sleep phase (Cajochen et al., 2005; Wahl et al., 2019). However, the substantial direct effect that remained after accounting for sleep quality, with $\beta = -0.24$ representing 41.5 percent of the total effect, indicates that blue light's association with productivity is not solely mediated by sleep. This direct pathway is consistent with evidence that blue light exposure during study sessions reduces reading speed and comprehension through direct visual fatigue mechanisms, including accommodative strain and reduced contrast sensitivity (Cajochen et al., 2005). Additionally, content-related cognitive interference and eye fatigue may impair reading efficiency independent of sleep disruption (Roenneberg et al., 2019).

The finding that blue light mitigation interventions, including Night Mode and blue light-blocking glasses, were associated with meaningful GPA differences ranging from 0.18 to 0.31 GPA points is particularly noteworthy from a practical standpoint. These interventions are low-cost and technologically accessible for Indonesian students across income levels; Night Mode is available at no cost on all modern operating systems. The magnitude of benefit associated with combined intervention use, 0.31 GPA points, is comparable to the effect of small-group tutoring interventions and substantially larger than many technology-based academic interventions (Okano et al., 2019). However, it is important to emphasize that these findings are correlational rather than causal. Users of protective interventions may differ from non-users in health consciousness, study habits, or other unmeasured characteristics that could independently influence both sleep quality and academic outcomes.

Several alternative explanations for the observed associations warrant consideration. First, the relationship between blue light exposure and sleep quality may be confounded by chronotype, the individual preference for morning or evening activity. Evening-type individuals (night owls) may be more likely to engage in nighttime screen use and may also be predisposed to poorer sleep outcomes independent of blue light exposure (Roenneberg et al., 2019). Second, socioeconomic status could influence both device access and sleep environment, including bedroom light exposure from external sources. Third, psychological arousal from content engagement, particularly from social media or emotionally charged academic material, may contribute to sleep disruption beyond the physiological effects of blue light alone. Exelmans and Van den Bulck (2016) demonstrated that pre-sleep passive screen use, such as streaming and social media scrolling, had stronger negative effects on sleep than active screen use such as coursework and reading, partly mediated by psychological arousal rather than blue light per se. In the digital learning context, students frequently toggle between academic platforms and social media, making it difficult to isolate the specific contribution of blue light from content-related arousal. Reverse causation also represents another important consideration. Students with pre-existing sleep difficulties may be more susceptible to nighttime screen use, either because they are awake and seeking stimulation or because they use devices as a coping mechanism for sleep-related distress. Similarly, students with lower academic performance may experience greater academic stress, leading to increased nighttime screen use for coursework completion, which in turn disrupts sleep. Without longitudinal data, we cannot establish temporal precedence or exclude the possibility that the observed associations are bidirectional.

Several limitations of this study merit consideration. First, the cross-sectional design precludes causal inference. Throughout this manuscript, we have therefore used associative language, such as "is associated with" and "was significantly related to," rather than causal language such as "causes" or "leads to," to reflect this limitation. Second, the lux-meter approach to blue light quantification, while validated against spectrophotometric measurements with r = 0.89 in a pilot study, represents indirect measurement rather than direct measurement of corneal irradiance. Direct spectrophotometry at the cornea would provide more precise quantification of blue light exposure but was infeasible at this sample scale. Third, the sample is limited to three universities in Java, Indonesia's most populous island. Students from outer islands with different infrastructure, device access, and cultural sleep practices may experience different patterns of digital learning and sleep behavior. Generalization of findings to the broader Indonesian university population should therefore be made cautiously. Fourth, the combined intervention group in the protective interventions analysis consisted of only 12 participants, which limits the statistical power and precision of estimates for this subgroup. Although sensitivity analyses using non-parametric tests confirmed the robustness of findings, these results should be validated in larger samples before drawing firm conclusions. Fifth, self-reported sleep quality using the PSQI may be subject to recall bias and social desirability bias. However, the PSQI has been well-validated in Indonesian populations with sensitivity of 89.6 percent and specificity of 86.5 percent for clinical sleep disorder (Bertolazi et al., 2011), which provides some reassurance regarding the reliability of these measurements.

Despite these limitations, this study makes several important contributions to the literature. It is the first to simultaneously examine the mediating role of sleep quality in the blue light-productivity relationship using both objective GPA and validated cognitive performance measures in an Indonesian university population. It also provides the first stratified analysis of combined protective interventions in the Indonesian digital learning context. These findings have practical implications for institutional digital wellness policies in Indonesian higher education, particularly within the framework of the *Merdeka Belajar-Kampus Merdeka* (MBKM) agenda. Universities may consider promoting awareness of blue light mitigation strategies, encouraging the use of Night Mode and blue light-blocking glasses during evening study sessions, and incorporating sleep hygiene education into orientation programs. However, given the correlational nature of the evidence, these recommendations should be implemented as part of broader wellness initiatives rather than as mandatory policies until further experimental evidence is available.

CONCLUSIONS

This study provides comprehensive cross-sectional evidence that pre-sleep blue light exposure from digital devices is significantly and negatively associated with sleep quality and academic productivity among Indonesian university students in the digital learning era. Students with high pre-sleep blue light exposure, defined as more than 3 hours per night, had significantly worse PSQI scores (8.6 versus 4.1), 1.5-hour shorter sleep duration, and 0.63 GPA points lower academic performance compared to low-exposure peers, with a large effect size (Cohen's d = 1.67). Blue light exposure explained 18.3 percent of GPA variance above and beyond demographic and stress covariates, with sleep quality partially mediating 41.5 percent of this association. Cognitive measures including TMT-B and Digit Span Backward confirmed objective executive function and working memory impairment in high-exposure students, independent of subjective reporting bias. Blue light mitigation interventions, including Night Mode and blue light-blocking glasses, were associated with significantly better sleep and GPA outcomes, with combined use showing the largest benefit of 0.31 GPA points improvement. However, given the correlational nature of the evidence, these findings should be interpreted cautiously.

The 71.3 percent prevalence of poor sleep quality observed within the participating institutions suggests a notable concern that warrants attention from university administrators and educators. Systematic digital wellness programs may be considered within MBKM curriculum frameworks at these and similar institutions. However, it is important to emphasize that the sample was limited to three universities in Java, Indonesia's most populous island, and may not be representative of students from other regions with different infrastructure, device access, and cultural sleep practices. Generalization of these findings to the broader Indonesian university population should therefore be made cautiously. Future research should employ longitudinal designs with objective polysomnographic sleep measurement and randomized intervention arms to establish causal pathways and optimize evidence-based digital wellness interventions tailored to the Indonesian higher education context. Multi-site studies across Indonesia's diverse regions are needed before broad policy recommendations can be made.

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