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New Lighting Technologies in Workplaces: A Narrative Review of Developments and Challenges

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ABSTRACT

Background: Modern workplace lighting has progressed beyond basic illumination, incorporating human-centric and smart technologies to enhance occupational health, performance, and sustainability. This narrative review integrates interdisciplinary findings to examine recent developments, benefits, and challenges associated with emerging workplace lighting technologies.

Methods: Literature published between 2015 and 2025 was collected from PubMed, Scopus, Web of Science, and IEEE Xplore, focusing on peer-reviewed journals, books, and conference proceedings. Out of 251 sources identified, 51 peer-reviewed articles were selected based on LED systems, human-centric lighting (HCL), and IoT-based controls in office, healthcare, and industrial workplace settings. The selected studies were thematically organized to address technological, health-related, and sustainability dimensions.

Results: IoT-driven smart lighting systems have demonstrated potential energy savings of up to 80%; however, challenges such as high installation costs, user resistance, and limited research in non-office environments remain. Ongoing debates concern the health benefits of HCL and the need for standardized metrics, such as melanopic equivalent daylight illuminance (MEDI). Evidence indicates that LED-based, tunable HCL can enhance sleep, mood, and cognition by aligning artificial lighting with circadian rhythms.

Conclusion: Emerging lighting technologies hold transformative potential for creating healthier and more sustainable workplaces. However, critical gaps persist in long-term studies, inclusive design approaches, and user adoption. This review provides a holistic framework linking technological innovation, occupational health, and environmental sustainability, and advocates for evidence-based, human-centered lighting strategies in occupational setting.

KEYWORDS: *Circadian Adaptation; Visual Ergonomics; Smart Lighting Systems; Occupational Health; Workplace Design; LED Technology; Energy Efficiency; Human-Centered Lighting*

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INTRODUCTION

Lighting significantly influences psychological health, cognitive function, and organizational productivity, in addition to providing basic visual performance in work environments. In modern workplaces such as hospitals and corporate offices, lighting systems must balance environmental sustainability, human health, and energy efficiency. Beyond mere brightness, lighting has evolved into a deliberate design element with measurable impacts on employee mood, visual comfort, circadian rhythms, and overall productivity. As industries transition toward smarter, greener, and more human-centered environments, architects, facility managers, occupational health specialists, and organizational decision-makers must recognize and address the complex role of lighting [1-4]. The evolution of workplace lighting has progressed from simple, static solutions to today's dynamic, tunable systems. For much of the 20th century, incandescent and fluorescent fixtures dominated, with limited consideration of spectral composition or biological effects, although they provided practical advantages in terms of cost and uniformity. Over the past five years, however, LED-based tunable white lighting has gained rapid traction. A 2021 laboratory study by Shackelford and Meier demonstrated that tunable white LEDs significantly improved concentration and reduced fatigue among office workers [5]. In a clinical setting, Schledermann et al. (2023) reported improved visual comfort and greater staff satisfaction following the implementation of a circadian-adjusted lighting system in hospital wards [6].Furthermore, Zhou and Pan (2023) demonstrated that specific lighting conditions can reduce cognitive strain and mental fatigue during reading task [7]. These pivotal studies illustrate how recent technological innovations have transformed our understanding of workplace lighting—shifting it from static and generic to dynamic, adaptive, and physiologically meaningful.

Today's interest in workplace lighting is driven by contemporary challenges, including energy conservation mandates, hybrid work models, and increasing concerns regarding mental health and well-being. In the post-pandemic era, fluctuating occupancy patterns require lighting systems that can adapt to variations in usage and daylight availability. Evidence from healthcare and control-room environments indicates that night-shift staff experience improved alertness and mood under circadian-adjusted lighting compared with traditional systems (Schledermann et al., 2023) [6].

Lighting has become a central consideration in modern office planning, driven by recent changes in workplace design associated with hybrid work practices, a growing emphasis on well-being, and sustainability requirements. Interest in healthy indoor environments—particularly lighting that supports both biological functioning and visual comfort—has increased markedly since the COVID-19 pandemic [8]. Currently, smart lighting systems equipped with sensor-based controls and Internet of Things (IoT) integration are increasingly being implemented to reduce energy consumption and adapt to user needs [9]. Furthermore, research linking inadequate illumination to sleep disturbances and reduced cognitive performance among both office and shift workers has reinforced the importance of circadian lighting [10]. These evolving concerns, including Environmental, Social, and Governance (ESG) frameworks, position office lighting as a multifaceted issue that extends beyond technical considerations, linking it to sustainability objectives, user-centered design, and occupational health [8]. Despite the growing number of publications in this domain, few reviews have comprehensively integrated technological, physiological, and organizational perspectives. Most existing works emphasize either energy efficiency or health-related outcomes in isolation, leaving a conceptual gap in understanding how these domains intersect within real workplace contexts. This narrative review therefore addresses this gap by synthesizing evidence across disciplines and evaluating how emerging lighting technologies are reshaping workplace design, worker well-being, and sustainability goals. This analysis seeks to address three interrelated questions that frame the discourse on workplace lighting technologies. First, how have the design, control, and functionality of lighting systems has evolved over time? Second, what are the benefits of systems such as human-centric and smart lighting—including improvements in comfort, health, and energy efficiency—and what limitations remain? Finally, what obstacles continue to hinder the wider adoption and implementation of these systems across diverse organizational settings? For example, while controlled experiments highlight the potential of adjustable lighting, real-world applications often fail due to design–user mismatches or budgetary constraints [11, 12]. Evaluating the innovative potential and current limitations of novel lighting techniques in work environments necessitates a thorough understanding of the relevant factors.

Unlike meta-analyses that focus primarily on quantitative comparisons, this review adopts a descriptive and critical approach to examine the implementation, perception, and evaluation of novel lighting technologies. It highlights interdisciplinary evidence, including case studies and pilot programs that demonstrate both the potential and complexity of lighting innovations in occupational settings. This narrative review aims to synthesize current knowledge on workplace lighting technologies by integrating findings from diverse fields, including engineering, psychology, chronobiology, and architecture [13, 14].

Therefore, the primary objective of this review is to synthesize and critically evaluate the literature on innovative workplace lighting technologies, offering an integrative framework that connects technical advancements with human and environmental outcomes. By contextualizing these findings, the review supports evidence-based decision-making among architects, engineers, occupational health professionals, and organizational leaders, as well as guiding future research and policy development. Ultimately, this analysis promotes a deeper understanding of workplace lighting as a multidisciplinary subject intricately connected to human behavior, technology, health, and the evolving nature of work.

MATERIALS AND METHODS

For this narrative review, the literature on novel workplace lighting technologies was obtained through a structured literature search, focusing on their impacts on sustainability, productivity, and occupational health. Keywords such as "workplace lighting," "human-centric lighting," "circadian lighting," "smart lighting," "LED lighting," "energy efficiency," "occupational health," "workplace productivity," and "sustainability" were used in combination with Boolean operators (AND for connecting core concepts; OR for combining synonyms; and NOT to exclude irrelevant topics).

For example, a representative search string in PubMed was:

("workplace lighting" OR "human-centric lighting" OR "circadian lighting") AND ("occupational health" OR "energy efficiency") NOT "residential."

Similarly, in Scopus, the following query was used:

TITLE-ABS-KEY ("workplace lighting" AND ("LED" OR "IoT-based" OR "smart lighting") AND ("sustainability" OR "productivity")).

Sources were retrieved from peer-reviewed journals, books, and conference proceedings through PubMed, Scopus, Web of Science, and IEEE Xplore databases. The literature search covered publications from 2015 to 2025. A total of 251 records were initially identified. After screening titles and abstracts, 122 records remained. Following full-text evaluation, 51 peer-reviewed articles were included in the final review based on methodological rigor and relevance to LED systems, human-centric lighting, and IoT-based controls in office, healthcare, and industrial workplace settings.

The screening and selection process was conducted primarily by the corresponding author. In cases of uncertainty, two co-authors with expertise in occupational hygiene and lighting engineering were consulted to ensure consistency and reliability. Discrepancies were resolved through discussion and mutual agreement.

Studies were included if they provided empirical, theoretical, or practical contributions relevant to workplace lighting, while studies focusing exclusively on non-occupational or residential contexts were excluded. Without performing quantitative data aggregation, the findings were thematically organized into four domains: technical developments, health benefits, energy efficiency, and implementation challenges. This structure created a coherent narrative for occupational health professionals, architects, and policymakers.

To enhance methodological transparency, a simple flowchart (Figure 1) was developed to illustrate the number of records identified, screened, and included in the final synthesis.

RESULTS

1. Background in Theory

The methods, tools, and design strategies employed to create artificial or natural lighting in indoor work environments are collectively referred to as workplace lighting. Recent frameworks have expanded this concept to include the biological and psychological effects of light exposure on human functioning, whereas traditional definitions primarily emphasized illumination for visual performance [15]. LED-based systems, tunable white and full-spectrum lighting, human-centric or circadian lighting, and smart lighting systems incorporating Internet of Things (IoT)–based controls and automation are all considered "novel lighting technologies" in this review [16]. In addition to ensuring adequate visual comfort and task visibility, these technologies contribute to improved human health, mood regulation, and energy efficiency [17]. To support both biological and

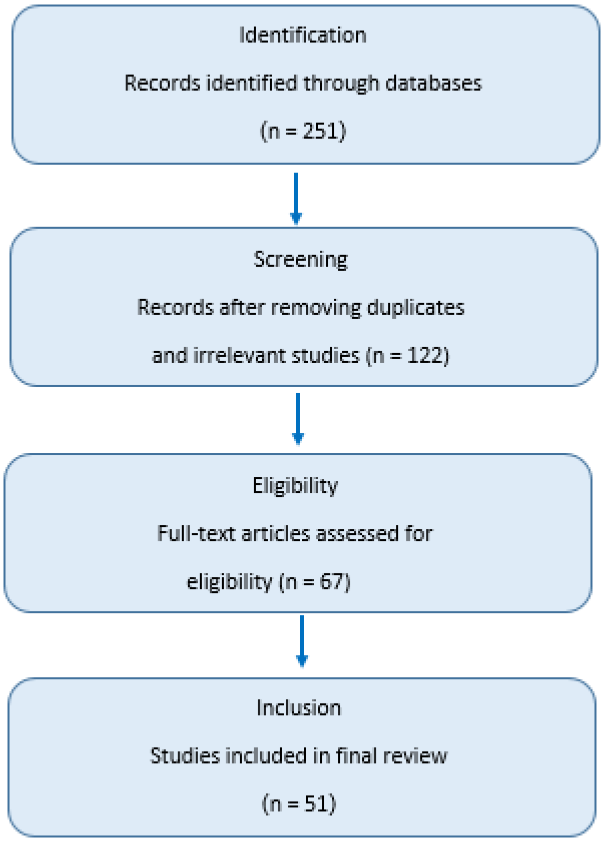

Figure 1. Flowchart illustrating the literature identification and inclusion process

organizational rhythms, tunable lighting systems, for example, can dynamically adjust color temperature and intensity based on the time of day or user behavior [18].

From the early 20th-century use of gas and incandescent lamps, to the widespread adoption of fluorescent lighting in mid-century office design, and finally to the emergence of solid-state LED lighting in the 21st century, the historical development of workplace lighting reflects key technological milestones [19]. LEDs have enabled significant improvements in longevity, energy efficiency, and design flexibility, paving the way for more advanced control systems as well as integration with sensors and automation platforms(20). The introduction of adjustable white LED systems, which allow variation in correlated color temperature (CCT) to mimic natural daylight cycles, marked a significant turning point [21]. The design and implementation of workplace lighting systems have also been shaped by regulations, including energy codes, WELL Building Standards, and occupational health guidelines [22]. These advancements have paved the way for recent developments aimed at better aligning illumination with sustainability goals and human physiological needs.

2 .Circadian and Human-Centric Lighting

Human-centric lighting (HCL) enhances workplace performance and well-being by aligning artificial light with circadian rhythms. By simulating the spectral and intensity variations of natural daylight, research indicates that HCL improves cognitive focus, reduces fatigue, and promotes better sleep quality [23, 24]. To mimic diurnal cycles and promote alertness during the day and rest at night, effective HCL systems employ tunable white LEDs that adjust correlated color temperature (CCT) and intensity [25, 26]. For example, dynamic lighting schedules that support circadian alignment—using warmer tones in the evening and cooler, higher-intensity light in the morning—have been shown to enhance productivity [27]. Critics highlight that outcomes vary across populations due to differences in age, health status, and cultural perceptions of light [28]. Scalability remains a challenge, as findings from small-scale studies often fail to translate across diverse workplace environments [29]. The extent of HCL's impact on health remains a subject of debate, with some arguing that its benefits are overstated in the absence of long-term evidence [30]. These discussions underscore the need for more extensive research and

Table 1. Smart/HCL systems against conventional lighting

Feature	Traditional Lighting	Smart Lighting / Human-Centric Lighting (HCL)
Control	Manual switch, fixed levels	Automated, sensor- and user-driven
Energy Efficiency	Low to moderate (incandescent/fluorescent)	High (LEDs with occupancy & daylight sensors)
Spectral Flexibility	Fixed color temperature	Tunable CCT for circadian alignment
User Autonomy	High manual control, limited flexibility	Varies: can be high if interfaces are intuitive
Health Outcomes	Focus on visual comfort	Includes circadian, alertness, sleep, mood
Sustainability	Limited focus on lifecycle impacts	Aligns with LEED/WELL; lower energy use and impact

standardized measures to validate the effectiveness of HCL [31].

3. Intelligent and Flexible Lighting Systems

By leveraging automation and Internet of Things (IoT) technologies, smart and adaptable lighting solutions optimize workplace illumination, enhancing both user experience and operational efficiency. Through sensor integration, these systems can adjust lighting based on user preferences, occupancy, or time of day, thereby reducing energy consumption and improving comfort [32, 33]. According to studies, smart lighting can reduce energy costs by up to 50% compared with conventional systems, primarily due to occupancy-based controls and dynamic dimming [34, 35]. As shown in Table 1, smart and human-centric lighting systems differ substantially from traditional lighting in terms of control, energy efficiency, health outcomes, and user experience

By enabling personalized lighting conditions, user-controlled settings—such as smartphone apps or customized interfaces—enhance user satisfaction (36). Nevertheless, challenges remain, including users' reluctance to adopt automation due to feelings of disempowerment or unfamiliarity with complex interfaces [37]. Adoption may be hindered by the learning curve associated with complex controls, particularly across diverse work environments. Variations in employees' technical literacy and inconsistent user training further complicate behavioral adaptation. To address these challenges and ensure the successful implementation of smart lighting solutions, user-friendly design and comprehensive training are essential [38].

4. Sustainability and Energy Efficiency

To achieve sustainability and energy efficiency in modern workplaces, LED and smart lighting solutions are essential. By significantly reducing energy consumption and enhancing occupant well-being through personalized lighting, these technologies facilitate green building certifications such as LEED and WELL [39]. Research indicates that LEDs can reduce energy consumption by up to 70% compared with traditional lighting, aligning with sustainability objectives [40]. Although these systems involve substantial upfront costs, businesses realize long-term savings through reduced energy bills and lower maintenance expenses. Return on investment (ROI) is often achieved within 2–4 years [41]. However, because LEDs rely on rare earth materials and their recycling is challenging due to complex procedures and insufficient infrastructure, environmental concerns remain. Enhancements in material sourcing and end-of-life recycling are essential to mitigate the environmental impact of these technologies and optimize sustainability [42].

5. Useful Consequences and Implementations

a. Examples of Real-World Applications or Cases

Human-centric lighting (HCL) and LEDs are examples of advanced lighting technologies that have been successfully implemented across various industries and demonstrated tangible benefits. According to a 2023 case study, a technology company in California installed LED systems in its offices, resulting in a 30% reduction in energy costs and improved employee well-being due to enhanced lighting quality [4]. Similarly, hospitals implementing HCL have observed faster patient recovery rates, as dynamic lighting that mimics natural daylight contributes to improved mood and sleep quality [43]. Smart lighting systems equipped with occupancy sensors in manufacturing settings have enhanced operational efficiency by reducing energy consumption in large-scale operations [34]. Facility managers have emphasized that user training is critical for the success of these projects, highlighting the importance of stakeholder engagement [38]. Phased rollouts have proven effective in addressing technical issues and ensuring smooth transitions [32]. While management prioritizes cost savings and low maintenance, employees consistently value the comfort and control provided by adjustable lighting [36]. These examples demonstrate how enhanced lighting contributes to occupant well-being and overall workplace functionality.

b. Pertinence to Experts, Teachers, or Policymakers

To equip future professionals for sustainable workplace design, engineering and design programs are incorporating smart lighting and LED technologies into their curricula [29]. To prepare future professionals for sustainable workplace design, engineering and design programs are incorporating smart lighting and LED technologies into their curricula [44]. By offering incentives for the retrofit of energy-efficient lighting, policymakers are leveraging these technologies to advance both corporate and national sustainability objectives, including net-zero emissions [2]. Aligned with climate objectives, European Union policies have actively encouraged the adoption of LED lighting in public buildings [45]. To optimize operational performance, professionals, including site managers, benefit from targeted training on the integration of IoT-enabled lighting solutions [46]. Growing recognition that enhanced lighting contributes to healthier and more sustainable workplaces is evident in these initiatives, which are influencing industry standards and shaping educational agendas across multiple sectors.

d. Difficulties in Applying Theory to Practice

Advanced lighting systems hold considerable potential; however, their implementation is often hindered by significant challenges. Small enterprises frequently face barriers to adopting LED and smart lighting solutions due to high initial costs and technical complexity, limiting their widespread uptake [1]. Another challenge is user resistance, as employees may be reluctant to adopt automated systems that reduce personal control or require familiarization with new user interfaces [37]. For example, a 2020 study in office environments found that employees misused smart lighting features due to overly complex controls, thereby diminishing the systems' potential for energy savings [34]. Adoption is further complicated by technical challenges, such as inconsistent light quality or incompatible software, particularly in older buildings [47]. User dissatisfaction can also arise from behavioral mismatches when lighting designs fail to accommodate the diverse needs of employees. To address these challenges and ensure both functionality and acceptance, it is essential to streamline user interfaces, provide comprehensive training, and align system designs with actual workplace requirements [48].

d. Views of Stakeholders: Employees and Facility Managers

Stakeholder perspectives reveal differing objectives in the implementation of new lighting systems. Facility managers tend to prioritize cost-efficiency and maintenance, selecting LEDs due to their durability and low energy consumption, which in turn reduces operating costs [41, 46]. However, employees place a high value on control and comfort, particularly favoring human-centric lighting (HCL) systems that enhance mood and productivity through adjustable settings [27, 42]. For example, a 2022 study conducted in healthcare facilities found that employees preferred dynamic lighting that adjusted according to shift schedules, enhancing alertness during night shifts [6]. Conversely, managers in production settings value smart lighting for its potential to reduce energy consumption in unoccupied areas, as evidenced by a factory upgrade implemented in 2021 [32]. Addressing the requirements of both stakeholders through intuitive design and clear communication is crucial for successful implementation [35]. Through targeted training programs and stakeholder consultations during installation, lighting systems can better address diverse expectations and deliver tangible benefits [47]. Figure 2 illustrates the key procedures for the effective deployment of smart lighting systems in office environments, emphasizing stakeholder engagement and iterative feedback.

This systematic approach addresses both human acceptance and technological implementation, reflecting recurring challenges highlighted in the literature [27, 36].

6. Advantages, disadvantages, open problems, and difficulties

Recent research on workplace lighting technologies highlights significant multidisciplinary integration, combining engineering, psychology, and health sciences to investigate the physiological and cognitive effects of light exposure. Innovative approaches now incorporate melanopic equivalent daylight illuminance (MEDI) and other circadian-sensitive metrics to quantify the non-visual effects of lighting [49]. Promising results from applied and experimental studies conducted in real-world workplaces—including offices, hospitals, and factories—have confirmed the practical applicability of these findings [13, 50]. For example, in night-shift

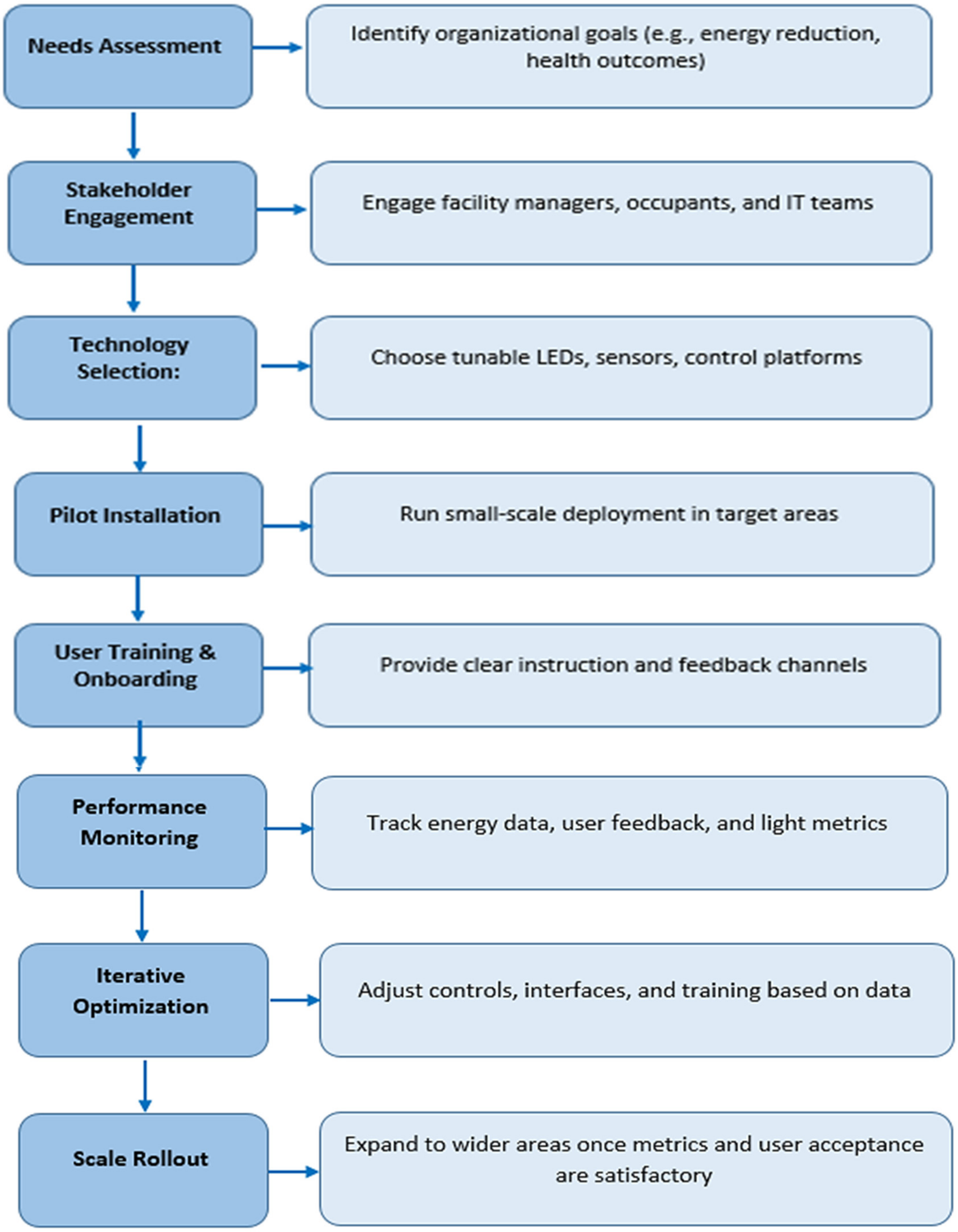

Figure 2. Flowchart: Smart Lighting Implementation Steps

simulations, Scott et al. reported improvements in mood and alertness under circadian-informed lighting conditions [10]. Similarly, Nagy et al. found that user-centered smart lighting reduced energy consumption while enhancing occupant comfort [36].

Despite promising results, the literature reveals persistent gaps. Most recent studies are short-term, involve small sample sizes, and are often conducted under controlled conditions, limiting the generalizability of their findings to diverse real-world contexts [30]. Furthermore, industrial and blue-collar environments, such as warehouses and construction sites, remain underrepresented in research, which continues to be predominantly focused on office settings [27]. Additionally, since light perception and preferences can vary significantly across locations and demographic groups, cross-cultural research is urgently needed [11]. Mainstream lighting research largely overlooks inclusive design considerations that account for age, gender, and cultural diversity [48].

The discourse surrounding office lighting systems continues to be shaped by ongoing debates. While human-centric lighting (HCL) is widely promoted for its potential health benefits, critics argue that the supporting scientific evidence remains either inconclusive or overstated, particularly in uncontrolled real-world environments [29]. Moreover, the comparison of system performance is further complicated by the lack of standardized criteria, such as those commonly applied in the evaluation of adaptive control strategies or spectral composition [31]. The appropriate balance between automated lighting control and user autonomy remains a subject of ongoing debate. While automation can enhance energy efficiency, excessive restriction of user control may negatively affect satisfaction and well-being [36, 37].

7. Significant Technological Developments and Their Effects on the Workplace

Workplace lighting has undergone significant technological advancements over the past decade, most notably through the introduction of adjustable LED systems capable of dynamically modifying spectral output to enhance both visual and non-visual outcomes, including alertness and cognitive performance [16]. Using virtual reality environments, Mostafavi et al. (2024) demonstrated that adjusting correlated color temperature and illuminance throughout the workday significantly improved cognitive task performance in controlled experimental settings [51]. Meanwhile, in real-world workplace settings, IoT-based smart lighting systems—such as the integrated illuminance management algorithm proposed by Obioma et al.—have achieved energy savings of up to 80%, highlighting a substantial shift toward sustainable illumination practices [52]. Daylight harvesting and machine learning hybrid solutions are becoming increasingly sophisticated. Colaco et al. (2023) investigated AI-powered daylight controllers designed to optimize both energy efficiency and user comfort, illustrating the growing complexity of adaptive lighting systems (53). Additionally, OCTOPUS and other holistic smart-building management systems have demonstrated energy cost reductions of over 14% while maintaining occupant comfort through the use of deep reinforcement learning to coordinate lighting, HVAC, and shading [54]. These innovations underscore the evolving role of lighting as both a resource-efficient and health-promoting component of workplace infrastructure.

The existing body of literature highlights a strong emphasis on human-centric and circadian lighting interventions in workplaces, particularly in office and healthcare settings. Most notably, Mostafavi et al. (2024) demonstrated in a controlled virtual reality study that dynamic modulation of illuminance and correlated color temperature significantly improved cognitive task performance and subjective alertness, in alignment with circadian principles [51]. In living-lab environments, Rolf et al. (2024) reported that increasing melanopic equivalent daylight illuminance (MEDI) in home-office settings enhanced alertness and improved psychomotor vigilance compared to baseline conditions [55]. Furthermore, Zhang et al. (2020) conducted a four-month dynamic lighting intervention in office environments and reported measurable improvements in worker experience, mood, and sleep quality [56]. These findings, which consistently utilize non-visual biological measures such as melatonin suppression and melanopic equivalent daylight illuminance (MEDI), signify a shift toward evaluating the physiological and psychological impacts of light exposure in real-world environments.

The widespread use of sensors, the Internet of Things, and automated controls in smart and adaptive lighting systems is another important theme. For example, Obioma et al. (2025) found that integrating occupancy and illumination sensors with adaptive dimming algorithms could result in up to 80% energy savings in office prototypes [52]. Aussat et al. (2022) reported that sensor-informed self-calibrating LED systems maintained desired illuminance levels while consuming approximately 40% less energy compared to standard LED lighting [57]. Furthermore, in an IoT lighting pilot, Konstantakopoulos et al. (2020) evaluated a Vickrey–Clarke–Groves mechanism, highlighting the importance of balancing automation with user preferences to optimize various satisfaction outcomes [58]. Despite variations in user experience and adoption culture, these case studies demonstrate a clear trend toward energy efficiency and enhanced user empowerment.

Lastly, the reviewed studies reflect a multidisciplinary approach to workplace illumination, incorporating perspectives from engineering, environmental psychology, chronobiology, and occupational health. Several experiments situate lighting within a broader sustainability and wellness agenda, often referencing certification frameworks such as LEED and WELL.

Table 2. Summary of Recent Studies on New Lighting Technologies in Workplaces

Study (Author, Year)	Setting	Intervention Type	Key Outcomes Reported	Metrics Used
Mostafavi et al. (2024) (51)	Virtual reality lab (office simulation)	Tunable white LED; variable CCT* & illuminance	Improved cognitive performance and alertness	Cognitive test scores; subjective alertness
Rolf et al. (2024) (55)	Home-based remote workspaces	MEDI**-enhancing dynamic lighting system	Increased alertness, improved sustained attention	Melanopic EDI; psychomotor vigilance
Zhang et al. (2020) (56)	Real office (4-month field study)	Dynamic LED lighting with automated tuning	Enhanced mood, better sleep quality, improved satisfaction	Sleep logs; mood questionnaires
Obioma et al. (2025) (52)	Smart office prototype (IoT lab)	Occupancy + illuminance sensor + adaptive dimming	80% energy savings, maintained visual comfort	Energy monitoring; user surveys
Aussat et al. (2022) (57)	Test office environment	Self-calibrating LED lighting system	40% energy reduction, consistent task lighting	Energy meters; lux readings
Konstantakopoulos et al. (2020) (58)	Smart office lab (economic control test)	AI-driven preference-aware system using VCG*** algorithm	Balanced user preference and automation in lighting schedules	Cost–benefit models; user input logs

*CCT = Correlated Color Temperature
**MEDI = Melanopic Equivalent Daylight Illuminance
***VCG = Vickrey–Clarke–Groves mechanism

However, most research remains concentrated on office environments, with limited investigations in industrial, educational, or cross-cultural contexts. This narrow focus contributes to inconsistent application across diverse workplace settings [55, 56]. Although frequently noted, differences in illuminance and spectral preferences across age groups and cultural backgrounds are rarely addressed in a systematic manner. The predominance of pilot and small-scale interventions also limits the extrapolation of findings to larger organizational contexts. Despite these variations in context and methodology, the literature consistently demonstrates that new lighting technologies enhance visual comfort, support circadian health, and optimize resource use. The key findings from recent research discussed in the updated results section are summarized in Table 1, which provides a concise comparison of lighting interventions, settings, outcomes, and key metrics.

DISCUSSION

The adoption of emerging lighting technologies in office settings reveals a complex interaction between technological innovation and human-centric design principles. Although individual variability and environmental factors influence this relationship, the reviewed literature highlights the potential of dynamic lighting systems, such as tunable LED solutions, to regulate circadian rhythms and enhance worker alertness. Notably, the effectiveness of these systems appears to depend on aligning spectral characteristics and light intensity with natural circadian cycles, reinforcing the notion that lighting should function as an adaptive environmental regulator rather than serving solely as illumination [59]. The apparent variation in results across studies highlights a crucial gap in applying circadian lighting principles to diverse workforce populations, reflecting the challenges of standardizing protocols and accounting for individual chronotypes. These complexities underscore the need for a multidisciplinary approach that integrates physiological and psychological knowledge with engineering innovations to optimize workplace illumination beyond conventional paradigms [60].

The variation in implementation strategies and technological complexity reported in the reviewed studies highlights the need for critical analysis of organizational and economic factors influencing the adoption of innovative lighting systems. Findings indicate a clear tension between high upfront investment costs and long-term benefits, particularly for small and medium-sized enterprises (SMEs), even though energy efficiency and sustainability remain primary drivers of LED and smart lighting adoption [61]. To address this socio-technical barrier, the literature suggests that policy incentives, governmental subsidies, and innovative financing mechanisms—such as performance-based contracts or shared investment frameworks—can help reduce the burden of initial costs. Such approaches may facilitate the adoption of energy-efficient systems in both private and public sectors, especially when accompanied by awareness programs and transparent communication of long-term benefits. Additionally, although intelligent control systems with real-time environmental adaptability have been shown to improve occupant comfort and productivity, their integration introduces operational complexity that may hinder broader adoption [62]. This paradox exemplifies the broader socio-technical challenges of workplace innovation, where organizational readiness, financial constraints, and technological feasibility must be balanced. The findings therefore underscore the need to align technological innovation with practical implementation frameworks by situating novel lighting technologies within an ecosystem of competing agendas and stakeholder interests [3].

From a theoretical standpoint, this paper illustrates how advances in lighting technology contribute to the development of conceptual models in occupational health and environmental ergonomics. The alignment of dynamic lighting and spectrum tuning with circadian biology reflects a shift toward an integrated paradigm in which environmental factors are actively adjusted to enhance wellness and cognitive performance (63). However, research also indicates that disentangling direct physiological effects from psychosocial mediators—such as workplace culture, perceived comfort, and safety context—is particularly complex in industrial and high-demand environments. The lack of field studies in such settings remains problematic because industrial workplaces differ substantially from offices in terms of task diversity, safety requirements, noise exposure, and environmental stressors. Addressing this gap is essential for developing evidence-based lighting standards that account for real-world conditions and protect both physical and cognitive health [64]. This intersection promotes a more nuanced, biopsychosocial understanding of lighting interventions, challenging oversimplified cause-and-effect assumptions. Consequently, the discussion extends beyond technical aspects and reframes workplace lighting as a multifaceted construct that integrates subjective perception with physical stimuli, thereby supporting theoretical frameworks that emphasize holistic person–environment interactions [65].

LIMITATIONS

As a narrative review, this study is subject to several methodological limitations. Although the literature search was structured and comprehensive, it was restricted to English-language publications, which may have excluded relevant regional or non-English studies. Additionally, the absence of a quantitative synthesis (such as a meta-analysis) limits the ability to estimate pooled effect sizes or assess heterogeneity across studies. Finally, study inclusion depended partly on author judgment, which may introduce selection bias despite the involvement of multiple reviewers in verification. Recognizing these limitations ensures transparency and contextual understanding of the synthesized finding.

CONCLUSION

This analysis highlights how LED, human-centric lighting (HCL), and IoT-enabled smart systems can enhance energy efficiency, circadian health, and visual comfort in workplace environments. Despite challenges such as high upfront costs and user resistance, evidence indicates that HCL improves sleep and cognitive performance, while smart systems significantly reduce energy consumption. By integrating perspectives from engineering, psychology, and chronobiology, the paper positions lighting as a multifaceted tool that contributes to a comprehensive understanding of workplace design.

In relation to the three guiding questions posed in the introduction, this review demonstrates that: (1) the design, control, and functionality of workplace lighting systems have evolved from static and uniform configurations to adaptive, tunable, and sensor-based technologies that respond dynamically to user needs and environmental changes; (2) human-centric and smart lighting systems offer measurable benefits—such as improved comfort, cognitive performance, and energy efficiency—while remaining limited by implementation costs and inconsistent standards across settings; and (3) barriers to widespread adoption persist, including financial constraints, lack of long-term field data, and limited integration of health-based lighting metrics into workplace design.

Future research should prioritize the use of standardized measures such as melanopic equivalent daylight illuminance (MEDI), the development of inclusive design approaches that address cultural and demographic diversity, and long-term studies across varied occupational contexts. Looking ahead, AI-integrated systems hold promise for holistic optimization, fostering healthier and more sustainable workplaces, while simplified interfaces and targeted incentives for small business retrofits may facilitate broader adoption.

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Conflict of Interest
The authors declare no conflict of interest.

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Manuscript Drafting: ZZ; PH
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All authors have approved the final manuscript and are responsible for all aspects of the work.

AI Statement
The authors confirm that no AI tools or services were used during the preparation of this work.

REFERENCES

1. Alstone P, Jacobson A. LED advances accelerate universal access to electric lighting. C R Phys. 2018;19(3):146-58.
2. Bera M, Das S, Garai S, Dutta S, Choudhury MR, Tripathi S, et al. Advancing energy efficiency: innovative technologies and strategic measures for achieving net zero emissions. Carbon Footprints. 2025;4(1).
3. Blume C, Garbazza C, Spitschan M. Effects of light on human circadian rhythms, sleep and mood. Somnologie. 2019;23(3):147-56.
4. Stephanidis C. The HCI discipline: past, present and future. In: Stephanidis C, editor. Foundations and fundamentals in human-computer interaction. Boca Raton, FL: CRC Press; 2024. p. 1-54.
5. Shackelford J, Meier A. Laboratory evaluation of tunable white LEDs for circadian lighting in commercial offices. 2021.
6. Schledermann K, Bjørner T, West A, Hansen T. Evaluation of staff's perception of a circadian lighting system implemented in a hospital. Build Environ. 2023;242:110488.
7. Zhou A, Pan Y. Effects of indoor lighting environments on paper reading efficiency and brain fatigue: an experimental study. Front Built Environ. 2023;9:1303028.
8. World Green Building Council. Health, wellbeing and productivity in offices: the next chapter for green building. London: World Green Building Council; 2014.
9. Baharudin N, Mansur T, Ali R, Sobri N. Smart lighting system control strategies for commercial buildings: a review. Int J Adv Technol Eng Explor. 2021;8(74):45-58.
10. Scott H, Guyett A, Manners J, Stuart N, Kemps E, Toson B, et al. Circadian-informed lighting improves vigilance, sleep, and subjective sleepiness during simulated night-shift work. Sleep. 2024;47(11):zsae173.
11. Aries MB, Aarts MP, van Hoof J. Daylight and health: a review of the evidence and consequences for the built environment. Light Res Technol. 2015;47(1):6-27.
12. Karyono K, Abdullah BM, Cotgrave AJ, Bras A, Cullen J. Human-centred approach in industry 4.0: lighting comfort in the workplace. In: Global Congress on Manufacturing and Management; 2021; Singapore: Springer; 2021.
13. Altomonte S, Allen J, Bluyssen PM, Brager G, Heschong L, Loder A, et al. Ten questions concerning well-being in the built environment. Build Environ. 2020;180:106949.
14. Konstantzos I, Sadeghi SA, Kim M, Xiong J, Tzempelikos A. The effect of lighting environment on task performance in buildings–a review. Energy Build. 2020;226:110394.
15. Belany P, Hrabovsky P, Florkova Z, Cajova Kantova N. The impact of workplace lighting on employee well-being and productivity: a measurement study. Syst Saf Hum-Tech Facil Environ. 2024;6:123-35.
16. Houser KW, Esposito T. Human-centric lighting: foundational considerations and a five-step design process. Front Neurol. 2021;12:630553.
17. Mesloub A, Alnaim MM, Albaqawy G, Alsolami BM, Mayhoub M, Tsangrassoulis A, et al. The visual comfort, economic feasibility, and overall energy consumption of tubular daylighting device system configurations in deep plan office buildings in Saudi Arabia. J Build Eng. 2023;68:106100.
18. Knoop M, Stefani O, Bueno B, Matusiak B, Hobday R, Wirz-Justice A, et al. Daylight: what makes the difference? Light Res Technol. 2020;52(3):423-42.
19. Boyce PR. The impact of light in buildings on human health. Indoor Built Environ. 2010;19(1):8-20.
20. Olajiga OK, Ani EC, Sikhakqane ZQ, Olatunde TM. A comprehensive review of energy-efficient lighting technologies and trends. Eng Sci Technol J. 2024;5(3):1097-111.
21. Frackson M, Eng B, Suvagu C, Eng P. White–tunable LED lighting: a literature analysis report. 2017.
22. Naser AA, Al-Mamoori HS. The role of interior design in achieving healthy workplaces according to lighting indicators of "WELL Standard". Int J Saf Secur Eng. 2023;13(5):859-68.
23. Chellappa SL, Gordijn MC, Cajochen C. Can light make us bright? Effects of light on cognition and sleep. Prog Brain Res. 2011;190:119-33.
24. Figueiro M, Steverson B, Heerwagen J, Yucel R, Roohan C, Sahin L, et al. Light, entrainment and alertness: a case study in offices. Light Res Technol. 2020;52(6):736-50.
25. De Kort Y, Smolders K. Effects of dynamic lighting on office workers: first results of a field study with monthly alternating settings. Light Res Technol. 2010;42(3):345-60.
26. Rea MS, Figueiro M. Light as a circadian stimulus for architectural lighting. Light Res Technol. 2018;50(4):497-510.
27. Van Duijnhoven J, Aarts MP, Aries MB, Rosemann A, Kort HS. Systematic review on the interaction between office light conditions and occupational health: elucidating gaps and methodological issues. Indoor Built Environ. 2019;28(2):152-74.
28. Cajochen C, Stefani O, Schöllhorn I, Lang D, Chellappa SL. Influence of evening light exposure on polysomnographically assessed night-time sleep: a systematic review with meta-analysis. Light Res Technol. 2022;54(6):609-24.
29. Houser K, Boyce P, Zeitzer J, Herf M. Human-centric lighting: myth, magic or metaphor? Light Res Technol. 2021;53(2):97-118.
30. Khademagha P, Aries M, Rosemann A, Van Loenen E. Implementing non-image-forming effects of light in the built environment: a review on what we need. Build Environ. 2016;108:263-72.
31. Bellia L, Bisegna F, Spada G. Lighting in indoor environments: visual and non-visual effects of light sources with different

spectral power distributions. Build Environ. 2011;46(10):1984-92.
32. Chew I, Karunatilaka D, Tan CP, Kalavally V. Smart lighting: the way forward? Reviewing the past to shape the future. Energy Build. 2017;149:180-91.
33. Pandharipande A, Caicedo D, Wang X. Sensor-driven wireless lighting control: system solutions and services for intelligent buildings. IEEE Sens J. 2014;14(12):4207-15.
34. de Bakker C, Aries M, Kort H, Rosemann A. Occupancy-based lighting control in open-plan office spaces: a state-of-the-art review. Build Environ. 2017;112:308-21.
35. Martirano L. A smart lighting control to save energy. In: Proceedings of the 6th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems; 2011 Sep 15-17; Prague, Czech Republic. IEEE; 2011. p. 132-8.
36. Nagy Z, Yong FY, Schlueter A. Occupant centered lighting control: a user study on balancing comfort, acceptance, and energy consumption. Energy Build. 2016;126:310-22.
37. Despenic M, Chraibi S, Lashina T, Rosemann A. Lighting preference profiles of users in an open office environment. Build Environ. 2017;116:89-107.
38. Pandharipande A, Caicedo D. Smart indoor lighting systems with luminaire-based sensing: a review of lighting control approaches. Energy Build. 2015;104:369-77.
39. Olabi AG, Shehata N, Issa UH, Mohamed OA, Mahmoud M, Abdelkareem MA, et al. The role of green buildings in achieving the sustainable development goals. Int J Thermofluids. 2025;25:101002.
40. Pašić E, Imamović N. Efficiency of LED bulbs compared to conventional bulbs - energy consumption study. 2020.
41. Davidovic M, Kostic M. Comparison of energy efficiency and costs related to conventional and LED road lighting installations. Energy. 2022;254:124299.
42. Qiu Y, Suh S. Economic feasibility of recycling rare earth oxides from end-of-life lighting technologies. Resour Conserv Recycl. 2019;150:104432.
43. Giménez MC, Geerdinck LM, Versteylen M, Leffers P, Meekes GJ, Herremans H, et al. Patient room lighting influences on sleep, appraisal and mood in hospitalized people. J Sleep Res. 2017;26(2):236-46.
44. Bühler MM, Jelinek T, Nübel K. Training and preparing tomorrow's workforce for the fourth industrial revolution. Educ Sci. 2022;12(11):782.
45. Bertoldi P. Overview of the European Union policies to promote more sustainable behaviours in energy end-users. In: Lopes M, Antunes C, Janda K, editors. Energy and behaviour. Amsterdam: Elsevier; 2020. p. 451-77.
46. Tan F, Caicedo D, Pandharipande A, Zuniga M. Sensor-driven, human-in-the-loop lighting control. Light Res Technol. 2018;50(5):660-80.
47. Sakhuja D, Ghai H, Bhatia RK, Bhatt AK. Management of e-waste: technological challenges and opportunities. In: Singh P, editor. Handbook of solid waste management: sustainability through circular economy. Singapore: Springer; 2022. p. 1523-57.
48. Heydarian A, Pantazis E, Wang A, Gerber D, Becerik-Gerber B. Towards user centered building design: identifying end-user lighting preferences via immersive virtual environments. Autom Constr. 2017;81:56-66.
49. Lucas RJ, Peirson SN, Berson DM, Brown TM, Cooper HM, Czeisler CA, et al. Measuring and using light in the melanopsin age. Trends Neurosci. 2014;37(1):1-9.
50. Golmohammadi R, Mehdinia M, Shahidi R, Darvishi E. Lighting effects on mental and cognitive performance - a systematic review. J Occup Hyg Eng. 2017;4(2):45-55.
51. Mostafavi A, Vujovic M, Xu TB, Hensel M. Impacts of illuminance and correlated color temperature on cognitive performance: a VR-lighting study. arXiv. 2024;arXiv:2406.02728.
52. Obioma P, Agbodike O, Chen J, Wang L. ISLS: IoT-based smart lighting system for improving energy conservation in office buildings. arXiv. 2025;arXiv:2503.13474.
53. Colaco SG, Varghese SG, Kurian CP, Kumar S. A state-of-the-art artificial intelligent techniques in daylighting controller: models and performance. Sci Technol Energy Transit. 2023;78:37.
54. Ding X, Cerpa A, Du W. Exploring deep reinforcement learning for holistic smart building control. ACM Trans Sens Netw. 2024;20(3):1-28.
55. Rolf H, Udovicic L, Völker S. Light exposure in home-based work: can a simple lighting system increase alertness? Light Res Technol. 2024;56(2):169-84.
56. Zhang R, Campanella C, Aristizabal S, Jamrozik A, Zhao J, Porter P, et al. Impacts of dynamic LED lighting on the well-being and experience of office occupants. Int J Environ Res Public Health. 2020;17(19):7217.
57. Aussat Y, Rosmanis A, Keshav S. A power-efficient self-calibrating smart lighting system. Energy Build. 2022;259:111874.
58. Konstantakopoulos I, Hamilton K, Murthy Y, Veeravalli T, Spanos C, Dong R. SmartSDH: an experimental study of mechanism-based building control. IEEE Syst J. 2022;16(4):6289-99.
59. Jalali MS, Jones JR, Tural E, Gibbons RB. Human-centric lighting design: a framework for supporting healthy circadian rhythm grounded in established knowledge in interior spaces. Buildings. 2024;14(4):1125.
60. Tähkämö L, Partonen T, Pesonen AK. Systematic review of light exposure impact on human circadian rhythm. Chronobiol Int. 2019;36(2):151-70.
61. Trianni A, Cagno E. Dealing with barriers to energy efficiency and SMEs: some empirical evidences. Energy. 2012;37(1):494-504.
62. Ahmed I, Asif M, Alhelou HH, Khalid M. A review on enhancing energy efficiency and adaptability through system integration for smart buildings. J Build Eng. 2024;89:109354.
63. Fisk AS, Tam SK, Brown LA, Vyazovskiy VV, Bannerman DM, Peirson SN. Light and cognition: roles for circadian rhythms, sleep, and arousal. Front Neurol. 2018;9:56.
64. Maier J, Zierke O, Hoermann HJ, Windemut I. Subjectivity of lighting perception and comfort: the role of preferences and expectations. Environ Behav. 2017;49(10):1105-27.
65. Plano SA, Casiraghi LP, Garcia Moro P, Paladino N, Golombek DA, Chiesa JJ. Circadian and metabolic effects of light: implications in weight homeostasis and health. Front Neurol. 2017;8:558.