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Review

Effects of outdoor artificial light at night on human health and behavior: A literature review☆

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A R T I C L E I N F O

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A B S T R A C T

The quality of life of human beings has improved tremendously through improved productivity, convenience, safety, and livability due to nighttime lights that illuminate outdoor work, leisure, and mobility. Recently, however, concerns have been growing over outdoor artificial light at night (ALAN) and its effects on human beings as well as ecosystems including animals and plants. This literature review aims to deliver a critical overview of the findings and the areas for future research on the effects of outdoor ALAN on human health and behaviors. Through a narrative literature review, we found that scientific research crucially lacks studies on the effects of outdoor ALAN on human behaviors and health, including social interaction, which may be more widespread compared to what is recognized so far. This review also highlights the importance of investigating the causal and complex relationships between outdoor ALAN, health, and behaviors with sleep as a key mediating factor. We elucidate that outdoor ALAN has both positive and negative effects on human life. Therefore, it is important for societies to be able to access facts and evidence about these effects to plan, agree to, and realize the optimal usage of nighttime lighting that balances its merits and demerits. Researchers in related areas of study must investigate and deliver the science of outdoor ALAN to various stakeholders, such as citizens, policymakers, urban and landscape planners, relevant practitioners, and industries. We believe that our review improves the understanding of outdoor ALAN in relation to human life and contributes to sustainable and thriving societies.

1. Introduction

The invention of electric light has revolutionized daily life with dramatic changes to light conditions at night (Falchi et al., 2011). Artificial light at night (ALAN) has added great value to our lives, as fundamental human activities (e.g., transportation, work, leisure) can continue uninterrupted even at night. The biggest benefit of ALAN is the visibility that it offers at night, which provides safety and convenience for people. ALAN has dramatically increased human productivity and the amount of spare time, thereby releasing humans from the regulation of work schedules. According to a report by International Dark-Sky Association (IDA), outdoor ALAN covers approximately 80% of the world population (IDA, 2016). The coverage rate of outdoor ALAN has been increasing due to increasing industrial development and human population in the world. Light at night includes both outdoor (e.g., street and field lights, cars, display advertising) and indoor lighting (e.g., room light, digital signage), as well as light from new sources such as electronic devices (e.g., computers, tablets, smartphones) during the last decades.

Along with the growth of light at night, the negative effects of excessive outdoor ALAN have been recognized by researchers and policymakers as "light pollution," which is defined as excessive or obtrusive artificial light due to improperly installed lighting (Gallaway et al., 2010). Although light pollution is a relatively modern social issue compared to other environmental pollution issues involving air and water, the fundamental disrupting effect of light on circadian systems was discovered over 60 years ago (Hastings and Sweeney, 1960) and have been investigated since then, mainly in medical and biological science.

Light pollution typically deteriorates dark skies and the calm visual

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environment at night that are vital for stargazing. Light pollution can also contribute to air pollution and global warming due to the energy waste caused by poorly designed or excessive usage of lights. Energy waste from excessive lighting can result in the unnecessary use of fossil fuels for generating electricity that emits air pollutants such as SO_2, NO_2, and CO_2. According to IDA, at least USD 3 billion is wasted on unnecessary outdoor lighting each year in the United States (US). This problem of unreasonable usage of outdoor lighting is all-pervasive in the world.

The more crucial effects of outdoor and indoor ALAN are on the behaviors and biology of species. According to IDA, ALAN affects the entire ecosystem (IDA, 2022). Excessive exposure to ALAN significantly deteriorates the functioning of biological clocks in animals and humans who experience sleep disturbance and serious health and behavioral problems, such as disrupted circadian rhythms in birds (Raap et al., 2017), insect movement, foraging, reproduction, and predation (Owens et al., 2020), and depression-like responses in mice (Fonken et al., 2009). Research has also shown that excessive exposure to outdoor ALAN is related to serious health and behavioral issues, such as cancer (Clarke et al., 2021; Garcia-Saenz et al., 2018; Lamphar et al., 2022; Ritonja et al., 2020; Zhong et al., 2020), infectious diseases such as COVID-19 (Argentiero et al., 2021; Meng et al., 2021), sleep problems (Boslett et al., 2021; Ohayon and Milesi, 2016; Paksarian et al., 2020; Patel, 2019; Xiao et al., 2020), depressive symptoms (Fonken et al., 2009; Helbich et al., 2020; Liao et al., 2022; Min and Min, 2018a), hyperactivity (Fonken et al., 2009), and altered reproductive behavior (Ouyang et al., 2018). Many reviews have discussed the adverse effects of lighting on circadian rhythm and sleep—general association (Aulsebrook et al., 2018; Touitou et al., 2017); extended health consequences (Tähkämö et al., 2019); individual differences (Chellappa, 2021); balancing daytime and nighttime light exposure (Fernandez, 2022)—mental disorders (Tancredi et al., 2022), cancer (Urbano et al., 2021; Walker et al., 2020; Wu et al., 2021), as well as on animals and natural ecosystems (Gaston et al., 2013; Gaston and Sánchez de Miguel, 2022; Russart and Nelson, 2018).

The immense benefits of ALAN might have masked its adverse side effects on health and the environment. Davies and Smyth (2018) recommended that ALAN should be a focus for global change research in the 21st century in the context of human health impact as well as culture and biodiversity conservation (Davies and Smyth, 2018). With increasing awareness of both the bright and dark sides of ALAN, optimal lighting design that balances these benefits and adverse effects to improve the environment should be explored. In particular, the impact of ALAN on human health and behaviors should be an important agenda for social and environmental sustainability that involves different policy and research areas, such as environmental assessment, environmental psychology, behavioral science, medicine, community and urban planning, land use, and energy (Cain and Phillips, 2021; Nilsson et al., 2013; Pothukuchi, 2021). Light exposure has differential impacts in terms of specific aspects of as well as elements in lighting technology; for instance, circadian disruption and visibility have been confirmed in animal and human research, particularly in indoor lighting settings. However, improving overall understanding of how ALAN affects human health and behaviors can involve the complex procedure of exploring evidence from both medical and social sciences, as human life and behavioral patterns are quite diverse depending on the geographical, climatic, cultural, and social contexts. Moreover, humans are exposed to a huge but differentiated variety of lights for a considerable part of their life. It is thus of particular importance to extend the focus of light research to psychology (e.g., perceptions, subjective well-being, place attachment), management (e.g., lighting design and layout that avoid excessive exposure while ensuring comfort and safety), and policy (e.g., regulations, standards, guidelines) to obtain useful implications for utilizing the benefits of artificial lighting in modern society while minimizing the adverse effects on health of animals, humans, and the overall environment. This study considers these perspectives in the review as distinguishing points—that is, review of both the beneficial and adverse effects of ALAN, integrative investigation of medical and social sciences, and extended focus toward management and policy aspects of ALAN.

Therefore, this study aims to provide a review of the literature on the impact of ALAN with a particular focus on human health and behavior under outdoor ALAN to fill the knowledge gap and to integrate the findings in extant research, as summarized in Fig. 1. The review consists of the following four sections: (1) characteristics and measurement techniques of outdoor ALAN; (2) impact of outdoor ALAN on human health and behaviors; (3) research and practices in managing outdoor ALAN; and (4) research questions materialized from the review for future research. We seek to compile useful findings from the literature for practitioners and experts in environmental and urban planning and public policies as well as researchers in areas such as environmental assessment, sustainability sciences, medicine, psychology, and land use.

2. Methodology

This literature review employed a narrative approach to cover broad issues on outdoor ALAN ranging from human health and behavior to management and policy. The literature search was performed using relevant keywords (e.g., "light pollution," "outdoor artificial light at night," "nighttime light," "outdoor lighting," "human," "health," "mental health," "sleep," "behavior," "management," and "policy," including combinations of these) in the research publication databases of Web of Science, PubMed, and Scopus. Relevant publications cited in the searched publications were also collected. The identified publications were screened according to relevance and the scope of this review based on the publication's title, abstract, and full text. In this process, less relevant publications were omitted, including those on technical and aesthetic specifications of lighting. Finally, 124 publications, which were published between 1996 and 2022, were included in this review.

3. Characteristics and measurement of outdoor ALAN

3.1. Definition and characteristics

Outdoor ALAN is defined as artificial lights in the outdoor environment at night, including stationary light emission sources such as lights outside houses, offices, shops, parking lots, sporting venues and other facilities, displays in commercial districts and non-stationary sources such as headlights in vehicles (Falchi et al., 2011; Helbich et al., 2020; Patel, 2019). The sources of light are mostly powered by electricity with a variety of devices such as fluorescent lights, incandescent lights, natrium gas lights, and light-emitting diodes (LED). Conventional types of lighting are being replaced with LEDs, which have advantages such as long life and higher energy efficiency but at the same time may have disadvantages in terms of the light's color and sharp brightness that induce discomfort glare and annoyance (Takahashi et al., 2007).

On the one hand, outdoor lighting in public spaces, such as parks and streets, improves perceived safety in the dark (Kaplan and Chalfin, 2022; Painter, 1996; Rahm et al., 2021) and reduces dark-related crime risks (Fotios et al., 2021). On the other hand, outdoor lighting for commercial purposes, such as advertisements and other attractions, is primarily aimed at promoting products and services (International Committee of Illumination (CIE), 2017). These commercial outdoor lightings are operated by facility tenants or owners usually under government acts and regulations, but not all countries or municipalities have such standards.

3.2. Measurement techniques

It is fundamentally essential to assess nighttime light situations to be able to examine the associations between light and human health and behavior. Various techniques have been used to measure outdoor ALAN in research and practice in lighting, urban and landscape planning,

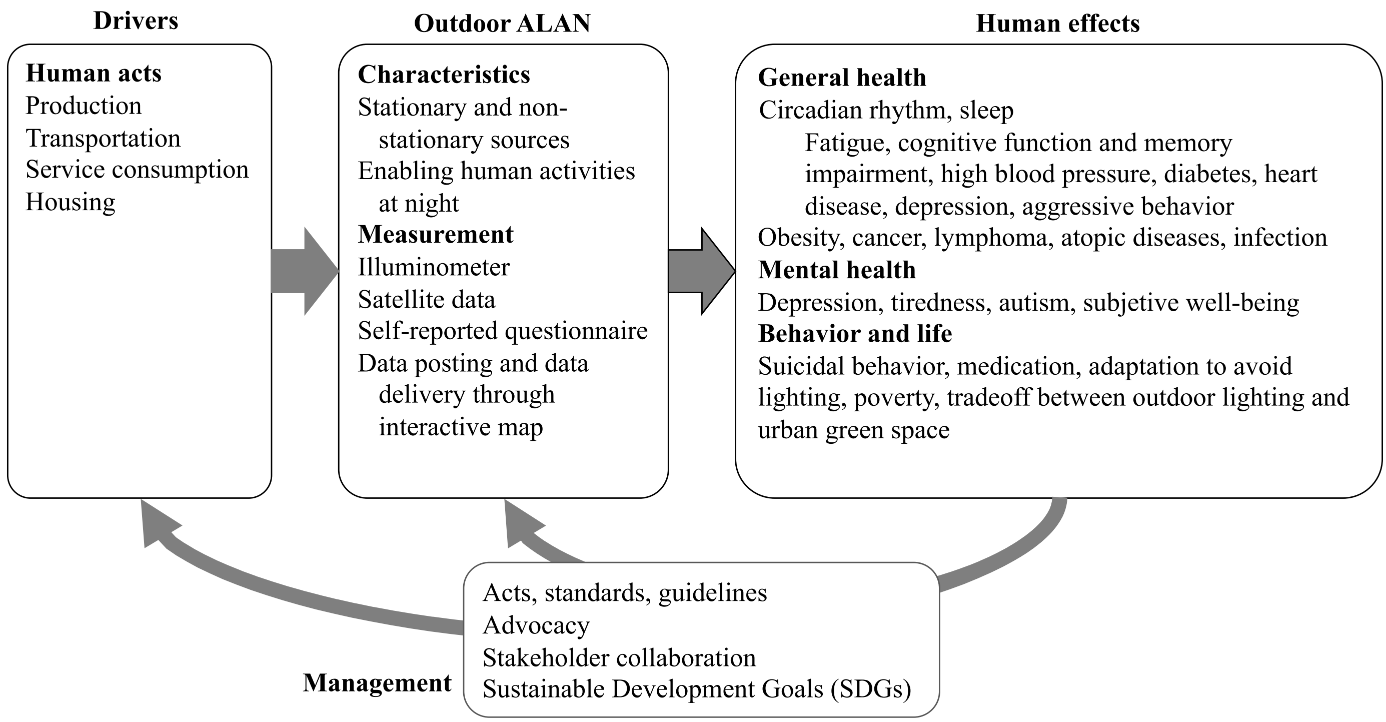

Fig. 1. Driving factors, situations, human effects, and management of outdoor ALAN.

remote sensing, and health and social sciences. This section details each of these techniques that were developed for different purposes and discusses their advantages and disadvantages in investigating effects of ALAN on human beings and on related issues. This section also helps understand how light data have been developed and employed in the research on the effects of light on human health and behaviors.

3.2.1. *Illuminometer*

The most traditional and convenient way to measure outdoor ALAN is to use an illuminometer. There are a variety of illuminometers from compact to highly functioning devices for measuring light intensity and frequency (i.e., color). A compact, portable illuminometer enables researchers to conduct field surveys at multiple points in a study area. For example, Ngarambe, Lim, and Kim (2018) implemented field measurement in over 200 sites in a province of South Korea using a handy illuminometer to examine the relationship between outdoor ALAN and land price as a proxy to income level (Ngarambe et al., 2018). Time-series data analysis is also possible with the actual measurement of

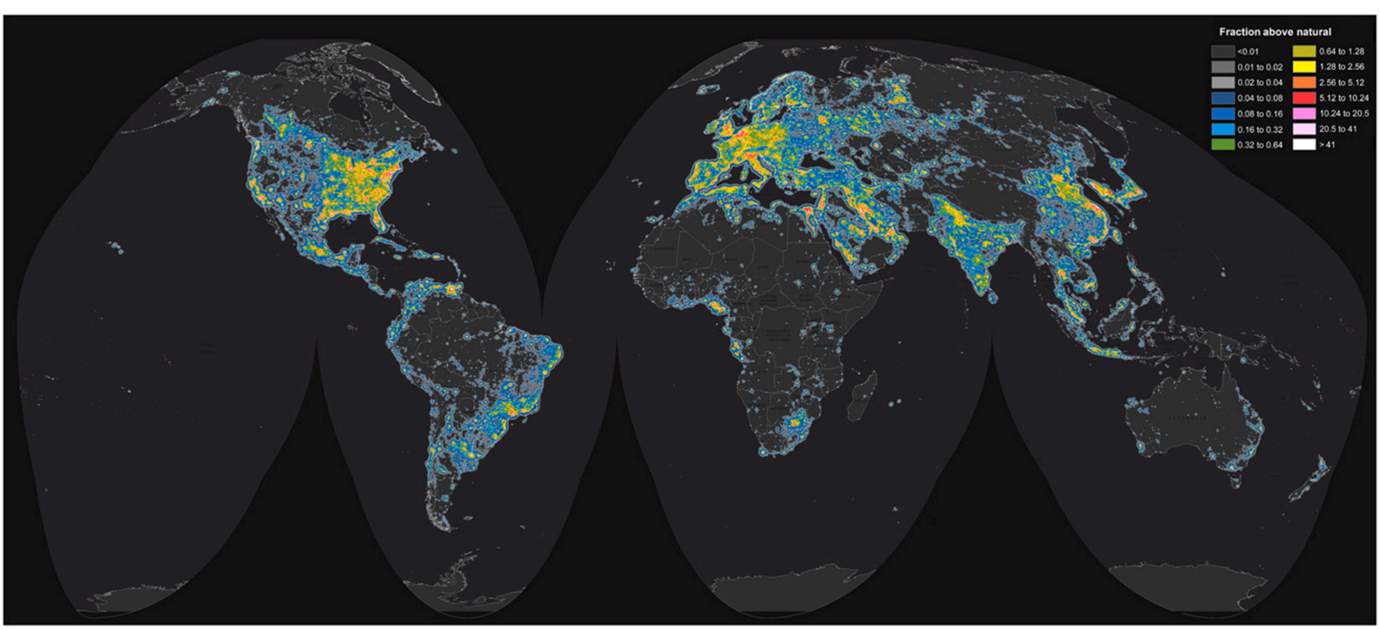

Fig. 2. World atlas of artificial sky brightness. Notes: Created using satellite data in 2013 by Falchi et al. (2016) (Falchi et al., 2016). Levels above natural sky brightness are indicated as follows: up to 0.01 (black); from 0.01 to 0.08 (gray to dark blue); from 0.08 to 0.64 (blue to green); from 0.64 and above under which the Milky Way is no longer visible (yellow); from Milky Way loss to estimated cone stimulation (red); and very high nighttime light intensities, with no dark adaption for human eyes (white). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

outdoor ALAN, especially in the case of regular monitoring installation. Cereghetti et al. (2020) used Sky Quality Meter (SQM) devices installed in the Environmental Observatory of Southern Switzerland (OASI) monitoring network to measure outdoor light in a southernmost Swiss region during 2011–2016 (Cereghetti et al., 2020).

3.2.2. Satellite data

Recently, more studies have utilized light data available from satellites to model artificial sky brightness. Cinzano et al. (2001) presented the first world atlas of outdoor ALAN using the satellite data of the US Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) (Cinzano et al., 2001), and Falchi et al. (2016) (Falchi et al., 2016) updated the outdoor ALAN world atlas using the satellite data of the Visible Infrared Imaging Radiometer Suite Day-Night Band (VIIRS DNB) sensor on the Suomi National Polar-orbiting Partnership (NPP) operated by the US National Oceanic and Atmospheric Administration (NOAA) (Fig. 2). This world atlas shows that large areas of the terrestrial globe have lost natural dark skies and that light pollution is not equally distributed but concentrated in densely populated and economically active regions such as the US, Europe, Japan, China, India, and Saudi Arabia. Furthermore, Falchi et al. (2019) developed a simple three-category evaluation system of “good,” “bad,” and “ugly” to rate light pollution in states and provinces in US and Europe based on their model using satellite data (Falchi et al., 2019). Such attempts help translate complex light pollution assessments using satellite data into an intuitive understanding of the relative severity of the pollution.

3.2.3. Self-reported questionnaire

Self-reported data of outdoor ALAN have also been used particularly in research that involves human perceptions about the neighborhood environment. For example, Coogan et al. (2020) collected categorical data on citizen’s perceptions about outdoor lighting in their residential areas based on a questionnaire in Ireland to find that Irish citizens considered public lighting to be the strongest light source near home regardless of urbanization levels (i.e., rural or city center) (Coogan et al., 2020). Several studies have used virtual outdoor ALAN environment in laboratory or online experiments to investigate participants’ light perceptions, acceptability of lighting levels, and reactions to hypothetical situations such as going out during different light settings (Boomsma and Steg, 2014; Kaplan and Chalfin, 2022; van Rijswijk and Haans, 2018).

3.2.4. Interactive online map using satellite or non-satellite data

The use of interactive online maps is growing for delivering nighttime data to the public. NASA Worldview Night Lights (NASA, 2022a) and NASA Blue Marble Navigator (NASA, 2022b) are among the most known interactive interfaces that process raw global satellite data into visual and numerical data comprehensible to lay people as well as scientists of different areas. Non-satellite data mapping tools are also available to understand night light distribution in the world and in specific areas. These tools generally enable users to find the levels of light in selected locations, thereby providing a bird’s eye view using different data sources. For example, the Globe at Night interactive map provides approximately 29,000 observations globally that are digitally reported by volunteers via its website and smartphone app using the eight-level magnitude scale (AURA, 2022). Visualization of outdoor ALAN can help public understanding of light situations, and these mapping tools could also provide detailed data on the lights at the city and district levels, which could help in planning to reduce light pollution at different levels.

3.2.5. Selection of measurement techniques

There are advantages and disadvantages to each technique for measuring outdoor ALAN. Illuminometer is excellent in being able to measure accurate illuminance on the field level and accurately tracking illumination change throughout a specific area or street and also relative differences in short periods (e.g., early versus late evening, weekday versus weekend). However, an illuminometer is not suitable for research that aims for extensive coverage of the geographical area to measure outdoor ALAN as it requires many data collection points. In this respect, satellite light images have more advantages as they can cover the large-scale light intensity distribution in several hundred-meter meshes. This helps researchers assess nighttime light at different scales from the municipality and district to country and global levels, enabling various analyses such as matching with large-scale survey data of demographic and health profiles of residents and comparing the nighttime light situations within and between countries. However, satellites do not provide light image data of the desired date and time and are not as accurate as the data measured with an illuminometer in the field. Self-reported data on light situations in specific locations or areas by respondents (e.g., residents, visitors, policymakers) have unique values in revealing stakeholders’ subject evaluation and perceptions about outdoor lighting. However, the evaluation criteria are usually set up with a simple categorical scale (e.g., 1 to 10 for too dark to too bright) that could be too simple to detect light range and be easily biased by personal factors such as sensitivity to outer stimuli and preferences regarding the lighting environment. Therefore, no single technique can be employed to measure outdoor ALAN as yet, but it is essential to understand the advantages and disadvantages of the available measurement techniques and select proper methods for research purposes.

4. Effects of outdoor ALAN on human health and behavior

4.1. General health

It is known that excessive ALAN exposure causes health problems both in humans and most animals (Kamrowski et al., 2015). Various effects of excessive ALAN exposure on health have been reported, such as increased risks of cancer, obesity, skin and other diseases, mood disorders, and sleep disorders. One of the most salient known effects of exposure to bright light at night on humans and animals is delay and disturbance in the biological clock and confusing circadian rhythm (Dumont and Beaulieu, 2007). Melatonin suppression is believed to disturb the circadian rhythm and balance of endocrine hormones, which leads to negative consequences in physical and mental health conditions (Nelson and Chbeir, 2018). Circadian rhythms are essential for the optimal functioning of organisms, and sleep-wake disruption or chronic dysregulation of circadian rhythms often leads to psychiatric and neurodegenerative diseases (Wahl et al., 2019). Most physiological dysfunctions are caused by the disturbed order of hormonal secretion during sleep, such as growth hormone, melatonin, and prolactin (Steiger, 2003). The order of secretion of hormones is important for maintaining healthy blood sugar levels and appropriate sensitivity of insulin, which could lead to obesity and diabetes (Touitou et al., 2017). Furthermore, the retina at the back of the eye acts as an important sensor for the brain to receive signals of light and is transmitted to the brain by the hypothalamic pathway, in which the signal suppresses the secretion of melatonin in the pineal gland (Claustrat et al., 2005). When melatonin production is disrupted, a whole chain of other chemical processes, including estrogen production, is affected (Cipolla-Neto et al., 2022).

Sleep is one of the most seriously affected aspects of human health due to ALAN. As discussed previously, excessive exposure to ALAN due to inappropriate usage of lights at night in animals delays circadian rhythm and disturbs sleep—that is, it causes prolonged sleep latency. In humans, this leads to a shortage of sleep time that affects sleep schedules because people usually have to wake up at a scheduled time for work or other activities regardless of delayed bedtime, which results in reduced work efficiency. A US study revealed that individuals living in areas under strong outdoor ALAN were more likely to report shorter sleep duration than those living under low outdoor ALAN (Xiao et al., 2020). Outdoor nighttime lights were associated with late bedtime among US adolescents (Paksarian et al., 2020) and among German adolescents (Vollmer et al., 2012) and delayed wake-up time, shorter sleep duration, and increased daytime sleepiness among the US general population (Ohayon and Milesi, 2016). Further, a previous study reported that an increase of 10 units of nighttime light resulted in an estimated reduction of approximately 6 min of daily sleep time and a 13.77% increase in the likelihood of reporting insufficient sleep (<7 h) (Patel, 2019). The cumulative impact of light exposure on sleep problems was found in the Finn national panel data study (Elovainio et al., 2021).

Sleep is not an isolated problem but affects many physical and mental conditions. Sleep disturbance increases the frequency of arousal at night, which results in excessive daytime sleepiness (EDS) and fatigue and impaired cognitive functions the following day (Kaida and Niki, 2014). Previous studies have reported the influence of sleep deprivation on the immune system (Ingiosi et al., 2013; Majde and Krueger, 2005; Trammell and Miller, 2013), memory encoding (Kaida et al., 2015; Simon et al., 2020; Tempesta et al., 2016) and consolidation (Rasch and Born, 2013; Simon et al., 2020), cognitive attention (Dinges et al., 1997; Kaida et al., 2008; Massar et al., 2019), high blood pressure (Calhoun and Harding, 2010; Guo et al., 2013), diabetes (Khalil et al., 2020) and heart disease (Wang et al., 2016; Zhang et al., 2021), depression (Byrne et al., 2019; Lustberg and Reynolds, 2000; Pandi-Perumal et al., 2020), and daytime anxiety (Schreck, 2021; Zhou et al., 2022). Several studies reported the negative influence of sleep deprivation on personality and behaviors such as introversion, aggression, and destructive and delinquent behaviors (Langsrud et al., 2018; Schreck, 2021), increasing the risk of accidents due to attentional lapses (Galina et al., 2021; Lucidi et al., 2013) and daily pro-social behaviors (Kaida and Kaida, 2017). To make matters worse, the effect of sleep deprivation accumulates as an amount of sleep deficit (van Dongen et al., 2003). Given that outdoor ALAN devices are installed and fixed in certain places, sleep problems and cognitive malfunctions could be chronic among the people living near excessive ALAN. It thus well explains that outdoor ALAN disturbs sleep in certain areas, as evidenced by the above-mentioned large population survey studies.

Disturbance in circadian rhythms due to outdoor ALAN increases the risks of metabolic dysfunction and obesity (Fonken et al., 2010). Liao et al. (2022) revealed a positive association between outdoor nighttime light and obesity and also daytime naps in the UK cohort data (Liao et al., 2022). Similar results on the association between ALAN and being overweight or obese were reported in many studies. Among middle-to-old aged American adults (Zhang et al., 2020), rural Brazilian adults (Benedito-Silva et al., 2020; Constantino et al., 2022), school-aged children and adolescents in China (Lin et al., 2022), and adults in South Indian villages, outdoor ALAN is a key urbanization indicator (Sorensen et al., 2020). Light exposure during sleep has been revealed to damage glucose homeostasis and affect cardiometabolic function (Mason et al., 2022). Several studies have shown a positive association between outdoor ALAN and different types of cancer, such as breast cancer from the Slovenian national survey data (Lamphar et al., 2022), breast and prostate cancer from Spanish regional survey data (Garcia-Saenz et al., 2018), and pancreatic cancer from the US data (Xiao et al., 2021). There are other types of disease risks such as lymphoma in the California Teachers cohort data (Zhong et al., 2020), atopic diseases in Chinese college students (Tang et al., 2022), and mild cognitive impairment in Chinese veterans (Chen et al., 2022). Similar associations between ALAN and health risks have also been reported in night-shift workers exposed both on and off work (i.e., indoor and outdoor). The risks include cancer and neurobehavioral, cardiometabolic, and reproductive functions (Lunn et al., 2017) and depression (Lee et al., 2017) as a result of decrease in overall melatonin amplitude and consequently, circadian disruption (Hunter and Figueiro, 2017). Several health studies on outdoor ALAN assume deterioration in the circadian rhythm as a mediating factor in the health effects of outdoor ALAN. Sleep, thus, could be the key to understanding the causal relationships between outdoor ALAN and human health and behaviors as exerting indirect effects through circadian disruption and sleep.

The evidence from different types of samples in different countries based on factors such as demographics, locations, and environmental characteristics suggests that outdoor ALAN could induce diverse health problems. The previous literature has provided sufficient evidence to suggest that the effects of ALAN on human health is plausible. However, these associations have not yet been comprehensively explained by the scientific evidence for mainly two reasons. First, not many studies examine *causal* effects of ALAN on human health. Second, there could be confounding factors in assessing the exposure and possible health effects of ALAN as suggested by previous studies—for example, being male in the effect of ALAN on obesity among children (Lin et al., 2022), and levels of ultraviolet B (UV–B) radiation as meteorological characteristics in the effect of ALAN on breast cancer (Urbano et al., 2021). The questions of causalities may be answered by lab experiment studies (Mason et al., 2022), cohort studies (Clarke et al., 2021; Elovainio et al., 2021; Esaki et al., 2019; Min and Min, 2018b; Zhong et al., 2020), and time-lagged questionnaire surveys with objective light data (Chen et al., 2022). These studies can capture changes in health and behaviors due to ALAN over time, but they remain unclear and require further investigation.

4.2. Mental health

Light in general can be a remedy to mental disorders when used appropriately (see Table 1 for the list of selected previous studies that examined effects of light on mental health and behaviors in humans). For example, light treatment is considered an option that reduces depressive symptoms. Properly controlled artificial light exposure can be used to treat some mood and sleep disorders (Dumont and Beaulieu, 2007), especially during dark winters in high latitude countries (Adamsson et al., 2018). A lab experiment study has shown that even a short-time (30 min) exposure to natural bright light during daytime is effective to increase positive emotions and reduce subjective sleepiness (Kaida et al., 2007). Similarly, many researchers have investigated the effectiveness of artificial or natural light in improving work and study efficiency and mood status in offices, factories, and schools primarily during daytime and indoors but also during nighttime and outdoors (Adamsson et al., 2018) as well as in reducing depressive symptoms and fatigue and improving sleep in case of daytime natural light exposure (Burns et al., 2021).

While light exposure indirectly affects physical and mental health through sleep, light can also affect mood by directly modulating the production of neurotransmitters such as serotonin (Blume et al., 2019). Previous studies report that outdoor ALAN exposure is correlated with depression levels. For example, a Korean study revealed that adults living in higher light pollution areas had a higher likelihood of depressive symptoms (Min and Min, 2018a). Additionally, a previous study with a representative sample of the Dutch population revealed a significant increase in depressive symptoms with increased outdoor ALAN after adjusting environment-related factors such as fine particulate matter ($PM_{2.5}$), urbanization, noise, land use diversity, greening, and social fragmentation (Helbich et al., 2020). Similarly, Liao et al. (2022) found depressed mood, low enthusiasm, and tiredness as having a positive association with outdoor ALAN in their UK sample (Liao et al., 2022). Furthermore, Xie et al. (2022) showed that higher outdoor ALAN exposure after and before birth is associated with a higher risk of autism spectrum disorder among children in Shanghai (Xie et al., 2022). Another study revealed that an increase in outdoor ALAN exposure due to shale gas plant development reduced sleep time and subjective well-being in a US sample (Boslett et al., 2021). In sum, the light condition at night is crucially important in ensuring good mental health conditions (Dumont and Beaulieu, 2007).

Table 1
Previous studies on the effects of light on human health and behaviors.

Study	Country of data collection	Year of data collection	Topic	Type of light	Type of data	Major results
Painter (1996)	UK	–	Fear of crime Walking	General outdoor ALAN	Field test Pre- and post- survey	Sensitively deployed street lighting can reduce in crime and fear of crime and increase pedestrian street use after dark.
Kaida et al. (2007)	Japan	2007	Mood status Subjective sleepiness	Indoor lighting Bright natural light	Experimental data	Brief (30min) natural bright light exposure improved pleasantness and reduced subjective sleepiness. A short nap shifts the mood status to positive/ favorable.
Vollmer et al. (2012)	Germany	2009–2010	Sleep	General outdoor ALAN	Satellite imagery data (National Oceanic and Atmospheric Administration (NOAA)) Survey data (Composite Scale of Morningness (MSFsc))	Adolescents living in brightly illuminated urban districts had a stronger evening-type orientation than those living in darker and more rural municipalities.
Boomsma and Steg (2014)	Netherlands	–	Perceived safety Acceptability	General outdoor ALAN	Laboratory data (virtual environment movie clips) Survey data (feelings of safety and the acceptability of reduced lighting levels)	Perceived safety mediated the effect of lighting on acceptability levels, suggesting that people can accept lower lighting levels when social safety is not threatened.
Ohayon and Milesi (2016)	US	2003–2011	Sleep Mental and organic disorders	General outdoor ALAN	Satellite imagery data (The Defense Meteorological Program/ Operational Line-Scan System (DMSP/OLS)) Telephone interview (The Sleep-EVAL General Population Survey)	Living in areas with greater outdoor nighttime lights was associated with delayed bedtime and wake-up time, shorter sleep duration, and daytime sleepiness, dissatisfaction with sleep quantity and quality, and the likelihood of having a circadian rhythm disorder.
Rudolph et al. (2017)	Denmark	2015	Percevied influence and annoyance Sense of place and darkness	Obstruction lights from wind mills	Survey data (perceptions of the lights and perceived influence and annoyance) Semi-structured interviews Observation data (wind turbines and their aviation obstruction lights)	The annoyance from flashing aviation obstruction lights was less severe in daylight and highest during dusk.
Adamsson et al. (2018)	Sweden	2008–2009	Mood Sleep-activity behavior	Office lighting Home lighting	Experimental data Questionnaire data (Positive and Negative Affect Schedule (PANAS), sleep-activity behavior, light sources at home)	Light radiation and the lit environment significantly influence human physiology, psychology, and health-related quality of life in addition to work performance and satisfaction.
Garcia-Saenz et al. (2018)	Spain	2008–2013	Cancer	Indoor and outdoor ALAN	Satellite imagery data (the International Space Station (ISS)) Survey data (Indoor ALAN, MCC-Spain)	Exposure to outdoor ALAN in the blue light spectrum was associated with breast and prostate cancer.
Min and Min (2018a)	Korea	2009	Depression Suicidal behaviors	General outdoor ALAN	Satellite imagery data (National Centers for Environmental Information) Survey data (2009 Korean Community Health Survey)	Adults living in areas exposed to higher levels had a higher likelihood of depressive symptoms or suicidal behaviors.
Min and Min (2018b)	Korea	2002–2013	Sleep Medication use	General outdoor ALAN	Satellite imagery data (National Centers for Environmental Information) Survey data (2002–2013 National Health Insurance Service-National Sample Cohort (NHIS-NSC))	Outdoor ALAN exposure was significantly associated with the prescription of hypnotic drugs in older adults. Outdoor artificial nighttime light may cause sleep disturbances.
Markvica et al. (2019)	Austria	2015–2017	Well-being Space and mobility behavior	Street lighting	Field test Survey data (open question)	LED street lighting positively affects perceived safety among pedestrians and vehicle drivers.
Patel (2019)	US	2014 and 2016	Sleep	General outdoor ALAN	Satellite imagery data (NOAA Earth Observation Group) Survey data (2014 and 2016 MMSA-level Behavioral Risk Factor Surveillance System Survey (BRFSS); 2016 release of the County Health Rankings)	An increase of 10 units of nighttime light resulted in an estimated reduction of about 5.59 min of daily sleep time and a 13.77% increase in the likelihood of reporting insufficient sleep (<7 h).
Benedito-Silva et al. (2020)	Brazil	–	Metabolic diseases	General outdoor ALAN	Motor activity and light exposure (wrist-worn actigraphy devices) Survey data (Baependi Heart Cohort Study)	More daytime light and a greater diurnal light difference are associated with a reduced risk of metabolic syndrome. Diurnal light differences were associated with BMI.
Esteky et al. (2020)	Germany and Canada	–	Pro-social behavior (donation)	Indoor lighting (LED and diffused/		Bright light amplifies individuals' dominant response to an opportunity

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Table 1 (*continued*)

Study	Country of data collection	Year of data collection	Topic	Type of light	Type of data	Major results
				indirect luminaires)	Experimental data Task data (self-construal) Survey data (Self-consciousness Scale)	to help others: greater consideration for others under bright light and donating more time and money.
Helbich et al. (2020)	Netherlands	2018	Depression Anxiety	General outdoor ALAN	Satellite imagery data (Day/Night Band on the Visible Infrared Imaging Radiometer Suite (VIIRS)) Survey data (self-administered Patient Health Questionnaire (PHQ–9))	A significant increase in depressive symptoms with increasing levels of outdoor ALAN.
Paksarian et al. (2020)	US	2001–2004	Sleep Mental disorder	General outdoor ALAN	Satellite imagery data (NOAA Earth Observation Group) Survey data (the National Comorbidity Survey–Adolescent Supplement (NCS-A)) In-person interview (mood, anxiety, and substance use disorder diagnoses)	Outdoor ALAN was associated with less favorable sleep patterns and mood and anxiety disorder in adolescents.
Portnov et al. (2020)	Israel	2020	Perceived safety	General outdoor ALAN	Survey data (light, feeling of safety)	The higher levels of illumination and uniformity positively affect the feeling of safety, while lights perceived as warm tend to generate a higher feeling of safety than lights perceived as cold.
Ritonja et al. (2020)	Canda	2005–2010	Breast cancer	General outdoor ALAN	Satellite imagery data (DMSP-OLS) and the Visible Infrared Imaging Radiometer Suite Day-Night Band (DNB)) Survey data (Population-based case-control study)	Outdoor LAN has a negligible or no effect on breast cancer risk.
Sorensen et al. (2020)	India	2003–2005	Cardiovascular disease	General outdoor ALAN	Satellite imagery data (DMSP-OLS) Survey data (Andhra Pradesh Children and Parents Study)	Increasing nighttime light intensity was positively associated with BMI, systolic blood pressure (SBP), and low-density lipoprotein (LDL) but not plasma glucose (FPG).
Svechkina et al. (2020)	Israel	2019	Perceived safety Walking	General outdoor ALAN	Field survey (chromameter) Survey data (feeling of safety)	Feeling of safety and public space lighting levels were positively associated, with this association exhibiting diminishing returns.
Xiao et al. (2020)	US	1995–1996	Sleep Physical activity Sedentary behaviors	General outdoor ALAN	Satellite imagery data (DMSP-OLS) Survey data (The NIH-AARP Diet and Health Study)	Residents living in areas with higher outdoor ALAN were more likely to report short sleep, which is more salient among residents of neighborhoods with higher poverty rates.
Zhang et al. (2020)	US	1995–1996	Obesity	General outdoor ALAN	Satellite imagery data (DMSP-OLS) Survey data (The NIH-AARP Diet and Health Study)	Outdoor LAN exposure rate can predict the risk of obesity in middle-aged and older adults, with a higher outdoor LAN exposure rate associated with a higher obesity rate 10 years later.
Zhong et al. (2020)	US	1995–2015	Cancer	General outdoor ALAN	Satellite imagery data (New World Atlas of Artificial Night Sky Brightness) Cancer cases (California Cancer Registry)	Outdoor ALAN was associated with an increased risk of non-Hodgkin lymphoma (NHL) and diffuse large B-cell lymphoma (DLBCL).
Boslett et al. (2021)	US	2000–2012	Community health Well-being	General outdoor ALAN	Satellite imagery data (DMSP-OLS) US shale play boundary data (US Energy Information Administration) Survey data (BRFSS)	The shale oil and gas boom has significantly increased light pollution in rural areas. Sleep deprivation and poor health (physical or mental) have both been associated with increased drilling.
Clarke et al. (2021)	Denmark	–	Breast cancer	General outdoor ALAN	Satellite imagery data (DMSP-OLS) Survey data (Danish Nurse Cohort)	A weak evidence of the association between LAN and breast cancer incidence but a suggestive association between LAN and estrogen receptor (ER) breast cancer.
Elovainio et al. (2021)	Finland	2010–2012	Sleep Health behaviors	Natural light	Natural light exposure (the Finnish Meteorological Institute) Survey data (Young Finns Study)	Bright light exposure for a long time can deteriorate sleep, with cumulative exposure inducing shorter sleep duration, sleep problems, and eveningness.
Meng et al. (2021)	US	2020	COVID-19	General outdoor ALAN	COVID-19 data (the Connecticut State Department of Public Health,	There is a significant positive correlation between LAN intensity

(*continued on next page*)

Table 1 (*continued*)

Study	Country of data collection	Year of data collection	Topic	Type of light	Type of data	Major results
					Open NY Program, Texas Health and Human Services, California Open Data Portal) Satellite images (NASA Earth Observatory)	and COVID-19 case rates per 1000. The circadian disruption caused by LAN may increase the COVID-19 infection rate by affecting the immune function of individuals.
Rahm et al. (2021)	Sweden	–	Perceived safety Mobility	General outdoor ALAN	Field test Semi-structured interview (open question)	The interaction of urban greenery and street lighting influences perceived safety and the neighborhood's walkability.
Xiao et al. (2021)	US	1995–1996	Pancreatic cancer	General outdoor ALAN	Satellite imagery data (DMSP-OLS) Survey data (NIH-AARP Diet and Health Study)	Higher estimated LAN exposure was associated with an elevated pancreatic ductal adenocarcinoma (PDAC) risk.
Chen et al. (2022)	China	2009–2011	Mild cognitive impairment	General outdoor ALAN	Satellite imagery data (Global Radiance Calibrated Night-time Lights Product) Survey data (The Mini Mental State Examination and the Montreal Cognitive Assessment)	Outdoor LAN was positively associated with a higher risk of mild cognitive impairment (MCI) in veterans.
Constantino et al. (2022)	Brazil	2012–2019	Obesity Sleep	Subjective light exposure	Munich Chronotype Questionnaire (Sleep routines and light exposure)	Living in more urbanized areas and higher intradaily variability (IV) of activity-rest rhythms were associated with an increased risk of belonging to the overweight or obese group.
Kaplan and Chalfin (2022)	US	–	Perceived safetyWillingness to pay	Street lighting	Online experimental data	Feeling safer under brighter street lights. The majority of respondents were willing to pay an extra annual USD400 to fund replacing dim yellow street lights with brighter LED lights.
Lamphar et al. (2022)	Slovakia	2003–2012	Breast cancer	General outdoor ALAN	Satellite imagery data (DMSP-OLS) Survey data (National Health Information Center of Slovakia)	Exposure to elevated light pollution levels could be a risk factor for breast cancer.
Liao et al. (2022)	UK	2006–2010	Mental well-being Obesity Physical activity Sleep pattern	General outdoor ALAN	Satellite imagery data (DMSP/OLS) Survey data (UK Biobank (UKBB))	The higher nighttime light emission was associated with higher air pollution, less green space, higher economic and neighborhood deprivation, higher household poverty and higher depressed mood, higher tiredness/lethargy, and obesity.
Lin et al. (2022)	China	2012–2013	Obesity	General outdoor ALAN	Satellite imagery data (DMSP-OLS) Survey data (Seven Northeastern Cities study)	Higher levels of outdoor LAN were associated with higher BMI Z-scores and greater odds of being overweight (including obesity) and obesity in school-aged children and adolescents.
Mason et al. (2022)	US	–	Sleep Health	Indoor lighting (dim light <3 lx and overhead room lighting 100 lx)	Experimental data	Compared with a dim light environment, one night of moderate light exposure during sleep increases nighttime heart rate, decreases heart rate variability, and increases next-morning insulin resistance.
Tang et al. (2022)	China	2018	Atopic diseases	General outdoor ALAN	Health examination (all skin diseases) Survey data (asthma, allergic rhinitis) Nighttime light (the remote sensing observed nighttime light)	Exposure to ALAN during adolescence may contribute to a higher risk of atopic diseases in young adulthood.
Xie et al. (2022)	China	2014	Autism spectrum disorder	General outdoor ALAN	Satellite imagery data (DMSP-OLS) Social Communication Questionnaire (SCQ)	Brighter ALAN exposures after and before birth were significantly associated with a higher risk of autism spectrum disorder.

4.3. Human behaviors related to outdoor ALAN

Compared to health, much less has been reported on the association between outdoor ALAN and human behaviors. However, recognizing that human behaviors are initiated by either personal or environmental factors or both (Duckworth and Gross, 2020), outdoor ALAN should be an important factor influencing human behaviors, explicitly and implicitly.

4.3.1. Positive effects

The advent of artificial light, after minimal usage over much of our long history, has radically changed human life, as people enjoy outdoor lighting for the perception of safety and convenience. Lighting prevents crimes and traffic accidents and enhances mobility and other outdoor activities such as jogging and exercise (Tavares et al., 2021). Painter (1996) discussed that the feeling of safety should be created by appropriate lighting in streets at night (Painter, 1996). Field questionnaire surveys using a smartphone app in selected cities in Israel revealed that higher illuminance is associated with the feeling of safety in urban public streets and natural parks (Portnov et al., 2020). A field questionnaire and observation study in Vienna found that well-illuminated streets, where lighting is uniform and comfortable (i.e., optimized LED lighting in the case of this study), facilitate a safe atmosphere and better feeling among pedestrians and vehicle drivers (Markvica et al., 2019). Virtual environment experiments that controlled confounding factors such as demographic characteristics and urbanization levels revealed that brighter street lighting leads individuals to feel safer (Kaplan and Chalfin, 2022). The feeling of safety under outdoor lighting in the dark increases the intention to walk and jog outside (Boomsma and Steg, 2014). A narrative study based on focus group discussions among neighbors in selected areas in Malmo, Sweden, reported that a proper combination of street lighting and urban greenery facilitates neighborhood walking in the evening (Rahm et al., 2021).

4.3.2. *Controversial effects*

There is ample recent evidence suggesting a reconsideration of the positive effect of outdoor ALAN on human perceptions and behaviors, referring to the non-linear relationships, dissociations, or negative relationships among them. The association between outdoor lighting and perceived safety may not be linear but logarithmic, as evidenced in a field study of public space lighting that showed a high positive association in extremely dark environments (i.e., 0–15 lux), with the curve increasingly flattening for brighter environments (i.e., over 15 lux) (Svechkina et al., 2020). This implies that outdoor ALAN critically contributes to the feeling of safety when very dark, but the light beyond the optimal illumination level becomes redundant and could induce the potential negative impact of outdoor ALAN. Moreover, feeling safer with outdoor lighting in the dark may not change outing behaviors at night (Kaplan and Chalfin, 2022). Physical activities such as walking and light exercise were not associated with nighttime light exposure (Liao et al., 2022). These findings suggest that there is still room for research on whether and how outdoor lighting improves perceived safety and facilitates evening outings including exercise.

Several other studies have revealed negative effects of excessive or unreasonable usage of outdoor lighting on behaviors, that is, hindering preferable behaviors or inducing undesirable behaviors. A Korean national survey-based study indicates the association between light pollution and suicidal behavior; that is, adults exposed to a higher degree of outdoor ALAN had more depressive symptoms or suicidal behavior, and probabilities of having these symptoms or behavior were approximately 30% higher in the highest quartile of outdoor ALAN compared to the lowest quartile (Min and Min, 2018a). Also, the same research group revealed that the use of hypnotic medication was positively associated with outdoor ALAN based on Korean national health survey data (Min and Min, 2018b). This study is salient not only because it supports the evidence of sleep disturbance due to outdoor lighting but also because it bridges health disturbance and behavior (i.e., use of drugs) under the potential effect of outdoor lighting. Other undesirable behaviors such as aggressive and impulsive ones through sleep disturbance due to excessive light have been reported in animal experiments and observations (Fonken et al., 2009). These undesirable effects of lighting on behavior through sleep disturbance could also occur in humans, as humans share a similar mechanism of influence of environment, sleep, and behavior with other animals (Aulsebrook et al., 2018; Gaston and Sánchez de Miguel, 2022; Touitou et al., 2017).

Outdoor ALAN can induce a negative impact on human behaviors in a longer and broader context. A questionnaire survey study investigated how residents reacted to flashing obstruction lights from an on-site wind turbine test site in Denmark based on a questionnaire survey (Rudolph et al., 2017). Residents reported a range of reactions from adaptive (e.g., using blinds and curtains) to coping strategies to mitigate annoyance (e.g., moving furniture inside house, talking with neighbors about the impact, joining protest); one of the salient reactions by the residents was to plan to move out, with one actual case, while about 15% considered doing so but did not go through with it by the time of the study. This study also pointed out that such behavioral changes due to ALAN would weaken the notion of the sense of place (place attachment), which is an essential factor for places to thrive. Moving out, if real or potential, as a negative consequence of ALAN, would be disastrous for a community. Some studies have presented concerns about outdoor ALAN in urban land use; for example, Stanhope et al. (2021) showed a tradeoff relationship between outdoor ALAN and urban green space, suggesting that reduced green space due to increasing nighttime lighting would result in deteriorating citizen behavior and health (Stanhope et al., 2021). The negative association between outdoor ALAN and human health in the urbanization context (e.g., Liao et al., 2022) is crucial in both daily and long-term life as mental health and physical symptoms would result in diverse and long-term consequences such as household and community safety and social engagement. All these findings imply that outdoor ALAN can have a long-term negative impact on human behaviors not only at the individual level but also at the community and societal levels.

5. Managing outdoor ALAN in relation to human health and behaviors

5.1. *Policies*

Initiatives by the International Committee on Illumination (CIE) for coping with light pollution include a technical guide on limiting the obstructive effects of outdoor lighting, referring to effects on people in daily life such as annoyance, discomfort, sleep disturbance, and astronomic observation (CIE150: 2017) (International Committee of Illumination (CIE), 2017). Several countries have regulations and technical standards on specific *elements* of nighttime lighting installations and conduct assessments in accordance with the guidelines by the CIE, its subordinate regional and national committees, or relevant industrial associations. The elements examined in previous studies include excessive glares from vehicle light devices against oncoming cars in the US, building light emission to outdoor and road lighting in Denmark, building light emission to outdoor in Iceland, street lighting, outdoor illuminated signs and advertising systems in Italy, energy efficiency in lighting in Spain, and road and street lighting in Sweden (Ministry of the Environment of the Czech Republic, 2022; National Highway Traffic Safety Administration, 2007; Widmer et al., 2022). However, while there have been growing concerns about the effects of outdoor ALAN on human health and behaviors, systematic management of outdoor lighting is lacking and thus, excessive lighting situations continue or are even growing in many countries.

Since the pioneer lighting policies concerning light pollution were introduced in 1942 in Tuscolo, Italy (Widmer et al., 2022) and in 1958 in Flagstaff, Arizona (Luz, 2009), several countries have established national- or municipal-level legislative acts, regulations, or guidelines to control outdoor ALAN more comprehensively in the context of light pollution (Table 2). In the US, at least 19 states have laws in place to reduce light pollution to control nighttime visual environment and reduce energy consumption. Dark night sky conservation for starry skies has been the most common purpose of controlling light pollution (e.g., Croatia, France, US, municipalities in Japan). Environmental considerations related to biodiversity and ecosystems (e.g., Croatia, France, Korea, municipalities in Japan) as well as proper energy use (e.g., Croatia, US, Slovenia) are increasingly centered on controlling outdoor ALAN. Only in a few cases like Croatia and Korea, legislations were formulated clearly indicating human health issues as one of the multiple purposes for controlling light pollution. Seoul, the capital of Korea, released a government ordinance to protect the quality of life of citizens from urban lighting in 2010. Japan released its first Guidelines for Countermeasures against Light Pollution in 1998 with the latest revision in 2021 covering human health impacts among others such as ecosystems and starry skies, but it is yet to be completed as legislation. Appropriate outdoor ALAN policies and systems that evaluate, monitor, and adjust nighttime lighting are necessary for protecting humans as

Table 2
National and regional legislations and guidelines related to outdoor ALAN.

Country	Year	Document title	Dcoument type	Types of ALAN	Coverage of ALAN impacts	Key regulations and instructions
Czech Republic	2021	Lighting manual	Guidelines	All outdoor lighting	–	Recommendations for public lighting, private lighting facilities or architectural light installations. New standards in progress to limit undesirable effects of lighting.
Croatia	2019	Law on Protection Against Light Pollution	Legislation	All outdoor lighting	Energy consumption Human health Natural ecosystem	Restrictions on searchlights and color lights among others with a relevant color temperature of 3000K (2200K in specific protected areas) and an upward luminous flux ratio ratio of 0.0%.
Denmark	2009	Nature Protection Act Decree 817/2018 (on adversiting in open landscape)	Legislation	Light advertising illumination	Human life Landscape Night sky	Avoid excessive light; shield all lights towards the sky and switch them off whenever not necessary. No light, retroreflective or moving including digital screens.
France	2018	Order of 27 December 2018 Relating to the Prevention, Reduction and Limitation of Light Pollution	Legislation	All outdoor lighting	Night sky Natural ecosystem Human health	Restrictions on an upward luminous flux ratio of less than 1% and a correlation color temperature of less than 3000K. It also stipulates the setting of light reduction time, recommends the use of human sensing sensors, prohibits the intrusion of light into the house, and inhibits glare
Italy (15 regions)	1997–	Regional laws against light pollution	Legislation	All outdoor lighting	Starry skies Energy consumption	Restrictions on lighting installations, illumination of public buildings, thresholds of light emissions. Stricter restrictions on protection zones.
Japan	2021	Guidelines for Countermeasures Against Light Pollution (Third Amendment)	Guidelines	All outdoor lighting	Plants and animals Human life Starry skies	Sets the upper light output ratio limits according to the light environment categories (E1: 0.0%, E2: 2.5%, E3: 5.0%, E4: 15%). Advises to keep color temperature of the illuminators below 3000K while cutting the upward light output. Road lighting lights, anti-crime lights and sports facilities lighting below 5000K.
Japan (Ibara City, Okayama)	2004	Ibara City Light Pollution Prevention Ordinance to Protect the Beautiful Starry Sky	Regulations	All outdoor lighting	Night sky	Turn off outdoor lighting after 10 p.m. till sunrise the following morning is encouraged. Outdoor lighting with an upward luminous flux ratio of 0.0% and less blue light associated with a color temperature below 3000K was set.
Japan (Kozushima Village, Tokyo)	2019	Kozushima Village Light Pollution Prevention Ordinance to Protect the Beautiful Starry Sky	Regulations	All outdoor lighting	Night sky Animals and plants Human life Energy consumption	Outdoor lighting is limited to an upward luminous flux ratio of less than 1% and a correlation color temperature of less than 3000K.
Korea	2012	Act on the Prevention of Light Pollution due to Artifical Lighting	Legislation	All outdoor lighting	Citizens' health Environment	Mayor/Governor may designate areas of light pollution including potential areas as lighting environment management areas (Class 1 to 4).
Korea (Seoul)	2010	Seoul Metropolitan Government Ordiance on Prevention of Light Pollution and Control of Urban Lighting	Legislation	All outdoor lighting	Citizens' quality of life Natural ecosystems	Lighting plan is required before installing outdoor lighting facilities in accordance with the light radiation standards prescribed by the rules for the permission to the lighting plan.
Slovenia	2007	Decree on limitation of light pollution of the environment	Legislation	All outdoor lighting	Starry skies Wildlife Energy consumption	Limits on upward light output ratio, intensity or time range of lightting in operation. No artificial nighttime light above horizen (i.e., 0.00 cd/klm).
Spain	2007	Regional decrees on protection of the nightlife; prevention of light pollution; protection of quality of the night sky against light pollution, etc.	Legislation	All outdoor lighting	Energy consumption Natural ecosystems Starry skies	Specific minimum requirements for energy efficiency in street lighting installations, more han 1 kW input.
United States	2010	Pattern Outdoor Lighting Code	Legislation	All outdoor lighting	Nighttime visual environment Energy consumption	General Outdoor Lighting Standards Outdoor Advertising Sign Lighting Standards Special Use Lighting Standards

Note: This table is based on multiple policy and legislation sources (ECOLEX, n.d.; Ministry of the Environment of the Czech Republic, 2022; Widmer et al., 2022).

well as animals and ecosystems from light pollution.

5.2. Hindering factors and emerging initiatives

Why has the management of outdoor ALAN not progressed to foster human health and behaviors? The key reason is that public awareness about light pollution is still low. For example, light pollution risk perception was lower compared to other environmental and health risks such as air pollution, climate change, and medical accidents in the Korean sample (Kim et al., 2015). This study also suggests that more knowledge about the risk enhances concerns about light pollution. According to a Finnish study on light pollution from road traffic, the general public is still unaware of this pollution issue, and raising awareness through different information strategies such as access to facts and ethical advocacy should be the first step to involving people to plan better outdoor lighting management (Lyytimäki et al., 2012).

Several international advocacy groups and platforms have promoted dark skies (i.e., less outdoor ALAN). IDA has provided information, tools, and resources to encourage individuals, policymakers, and industries to learn and act to reduce light pollution since its establishment in the 1980s. Also, the EU launched a light pollution initiative called STARS4ALL in 2016–2018 to develop a collective awareness-raising platform that aimed to eventually lead to new policies to end light pollution (EU-STARS4ALL, 2022). These advocacies have contributed to managing outdoor ALAN at different levels including policies to a certain extent, but their focus has been mainly to reduce the night sky glow for star observation and a calm environment, and the impact on human life has been largely untouched. This gap may be because of the teleological motive and clear ultimate goal (i.e., starry skies), and the cumulative scientific and practical knowledge base shared among dark sky advocacies and astronomical and related research (IDA, 2022) is growing, but it continues to be less among advocacy and research communities related to human life. While medical science has been increasingly contributing to understanding human life under outdoor ALAN with great interest, the light pollution advocacies are yet to bloom with human health impacts as the central focus as it is more difficult to translate scientific evidence and opinions into concrete and simple messages to evoke public awareness. Medical and social sciences also face issues of heterogeneous populations (e.g., age, income, general health, work, education, other environmental factors) in delivering universal health impact evidence, which requires further research accumulation and ethics. Considering these challenges, the dark sky agenda and research will continue to be important and can help mitigate health impacts by managing nighttime light.

To tackle light pollution, collaborative management frameworks have been recently proposed involving various stakeholders such as citizens, planners, policymakers, businesses, and scientists. Lyytimäki (2015) proposed a systems intelligence approach against light pollution, which insists on the importance of involving individuals at different levels of action through collaboration (e.g., learning about darkness, consumers' choices, influencing decisions) (Lyytimäki, 2015). A transdisciplinary light pollution regulatory framework was proposed by a more recent study to tackle the issue (Vega et al., 2021). Recent studies have discussed outdoor ALAN management under longer-term agendas such as the Sustainable Development Goals (SDGs), for example, achieving relatively human-centric Goals 3 (Good Health and Well-being) and 11 (Sustainable Cities and Communities) while also achieving Goals 7 (Affordable and Clean Energy), 14 (Life Below Water), and 15 (Life on Land) (Cucchiella et al., 2021; Tavares et al., 2021).

5. Discussion

This review offers several key topics for future research on outdoor ALAN related to human health and behaviors based on the developments in outdoor ALAN research and practices thus far. First, the development of an integrated methodology for detailed and accurate assessments of outdoor ALAN could be an important contribution to the research in this area. Although many technical tools including satellite light maps have been developed, the average nighttime data available from satellites is not detailed enough for an accurate estimation of individual ALAN exposure in intended timings and durations (Min and Min, 2018a). So far, it has been impossible to obtain satellite data on the continuous timing of lights being on, duration of lighting, and its colors; nevertheless, satellite data do help understand associations between ALAN and human health and life patterns at the district level (Xiao et al., 2020). Integrated ways of utilizing satellite light data and micro-level time lapse field measurement data could help researchers and policymakers have an overview of area-wise light pollution, while enabling comparisons with other areas and, at the same time, providing a detailed understanding of local dynamics of emittance of and exposure to nighttime light in the target area. Such detailed, objective information in a large target area is necessary for the holistic management of outdoor ALAN within a certain scale, such as a municipality and its subordinate areas by small blocks and streets. This is because light pollution is now counted as one of the growing environmental problems, alongside climate change and ecosystem conservation, in many countries. This is of particular importance taking into consideration the inseparable relationships between light pollution and these environmental problems through wasted energy and deterioration in urban wildlife and green space (Gaston and Sánchez de Miguel, 2022; Rodrigo-Comino et al., 2021; Stanhope et al., 2021).

Second, further research on ALAN related to health and behavior in humans needs to be conducted extensively to fully understand the association between outdoor ALAN and human life consequences. While many animal studies have been conducted, in both field and lab settings, that have contributed to understanding the potential impact of outdoor ALAN on humans, their validity for humans seems limited. To understand the impact of outdoor ALAN on humans, many factors should be considered including demographic and individual characteristics (e.g., age, gender, education, income, work time, sleep habits and regularity, history of sleep disorders, and other health conditions) (Muscogiuri et al., 2022; Sorensen et al., 2020; Xiao et al., 2020). Also, holistic research on light exposure impacts on humans is necessary at both individual and societal levels. This includes indoor and outdoor sources of light exposure at day and night as well as use of electronic devices (e.g., TV, computers, tablets, smartphones) (Heo et al., 2017; Muscogiuri et al., 2022). More detailed data on light-related habits as well health and lifestyle among individuals will also help understand how humans are sensitive to light impacts and how they tend to mitigate the impacts in daily life, such as bedtime habits (e.g., room lighting at home, use of curtains or eye masks, use of light-emitting devices such as TV, computer, and smartphone). The interaction of climate, greening, land use, and other environmental factors with ALAN would be also of great value in future research (Rahm et al., 2021; Stanhope et al., 2021). Several studies have partially overcome this issue, but there are still many more factors that need to be considered in lifestyle diversity such as work schedule, life-stage change, and voluntary and involuntary opportunities to be outside at night such as going out for leisure and exercise, commuting, and other daily life necessities. We can assume that people would give up or minimize going out voluntarily when they become aware that the degree of outdoor ALAN exposure is high because people would want to avoid its potential harm. The effect of outdoor ALAN exposure on going out at night could be one of the important topics to be investigated in future research.

Third, the diverse and widespread impact of outdoor ALAN on humans requires further investigation, especially the causal association between mental health and behavior. Previous studies, as reviewed in this paper, have found that excessive outdoor ALAN deteriorates physical and mental health in humans. Light pollution may increase depressive symptoms, which make people become less active in their personal lives, lose interest in their surrounding environment, and be less engaged in pro-social behaviors and activities with others. This review based on previous studies proposes that light pollution may trigger a negative spiral of reduced mental health, thereby impacting positive emotions, which could in turn lead to a decline in personal and social activities such as helping, sharing, comforting, and cooperating. Light pollution could also inhibit social activities by inhibiting people's sense of place and community among affected residents as suggested by a Danish study (Rudolph et al., 2017). Such a negative impact could critically deteriorate social ties and social capital in communities regardless of whether the setting is urban or rural. In this sense, outdoor ALAN is an important research topic across diverse areas including environmental health risks, environmental policy, urban and community planning, landscape planning, environmental education, and social and environmental psychology, and could offer beneficial findings for citizens and national- and municipal-level policymakers.

Finally, and related to the previous point, causal associations on the effects of outdoor ALAN on human health and behaviors could be a worthwhile subject in future research. Many previous studies are based on cross-sectional data with a strong assumption on the impact of outdoor ALAN on perceptions, health, and behaviors. This assumption seems plausible but needs to be tested with observed or self-reported panel data or laboratory or field experiments with properly controlled conditions. This is particularly important when complex and repeating associations are considered such as the negative spiral discussed earlier in this section. In turn, a proper outdoor ALAN management plan could be designed to create the positive spiral of having comfortable and safe outdoor ALAN with reduced but optimally designed illumination, enhancing health and subjective well-being, and engagement with the society, leading to the nurturing of social capital in communities as a wide-spread consequence of appropriate outdoor ALAN in the long run. Therefore, a research design that collects panel data and an analytical approach that is good for testing causal associations need to be developed. Integrating data collected in different formats (e.g., field light measurement, questionnaire surveys, and laboratory experiments) could be a challenge for conducting research in this perspective.

This review has several limitations. First, this work was conducted as a narrative and qualitative literature review and thus does not ensure completeness or non-arbitrary selection of the literature reviewed in this work. We believe that a narrative approach was a reasonable methodology in this review to cover broad, relatively new, and immaturely defined issues of human health and behavior and management and policy concerning outdoor ALAN; however, we may have overlooked relevant papers. With the accumulation of literature, future systematic literature reviews would overcome this problem. Second, this review did not fully consider the details of differences in human health and behavior investigated in each study, including confounding factors such as socioeconomic characteristics, urban greening, air pollution, and light elements. This may be examined in future research through a meta-analysis covering different factors including topics, methods, considered variables, and results on the (potential) effects of outdoor ALAN.

6. Conclusions

This literature review provides an overview of the state-of-the-art findings and future research agendas on the potential relationships between outdoor ALAN, human health, and behaviors. ALAN might be one of the triggers for poor physical and mental health and might lead to changes in daily life behaviors through changes in sleep states. This review suggests that the impact of ALAN on human behaviors may be more widespread including social interaction. Future studies should lead in investigating and delivering the science of outdoor ALAN to various stakeholders (e.g., citizens, policymakers, urban and landscape planners, relevant practitioners, and industries) to plan, reach a consensus on, and realize the optimal usage of nighttime lighting that balances its merits and demerits.

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