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Review

Artificial Light at Night (ALAN), a New Anthropogenic Pollutant

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Abstract

The simplest definition of light pollution (LP) is the presence of artificial light at night (ALAN) at inappropriate times, intensity, and inappropriate amounts and colors. All these parameters of anthropogenic light clearly indicate that the presence of ALAN can disrupt the proper functioning of not only humans but all organisms on Earth that have evolved in conditions of alternating day and night, closing within a 24-hour day. Cities are the primary source of LP, and the ever-increasing global urbanization makes LP one of the fastest-growing threats to our civilization. It is particularly dangerous because public awareness of its existence is exceptionally weak, as the presence of light is usually perceived as a good thing, generating safety and beauty, and it is difficult for people to understand that excess of light may turn against us. However, LP dysregulates the well-known circadian rhythms of humans and animals and disrupts normal plant physiology. Furthermore, in a light-polluted world, plant-pollinator relationships are also engendered, which can lead to disruptions in food chains. In this review, we will present various aspects of excessive-lighting and propose solutions to mitigate the increasing LP, considering the threats it poses to all living organisms.

Keywords: light pollution**;** artificial light at night; urbanization; circadian dysregulation; food chains disruption

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1. Introduction

The conditions of life on Earth have been shaped by its rotation, thanks to which the day is divided into light (L) and dark (D) periods - i.e. day and night, respectively. Proportion L:D varies seasonally, i.e., the length of night increases as the day becomes shorter. Every organism living on Earth is adapted to either the light (diurnal species) or dark phase (nocturnal species) of the day. This means that the metabolic rate and behavior of an animal differ depending on the phase of the day in which it is active or resting. We should also remember plants and their ability to photosynthesize, which takes place only in the bright phase of the day. This is the unique capability of plants (and some microorganisms) to produce organic matter (glucose) from inorganic precursors: water and carbon dioxide, and thus to start the food chain. However, apart from this period of photosynthetic activity, plants also need a night-time rest phase associated with reduced water loss, among other events. Thus, plants and animals, together with humans and microorganisms, constitute a biosphere, i.e. a global ecosystem adapted to these regularly changing L:D conditions, while only humans can influence and modify their characteristics, e.g. duration, intensity, color of light, etc. And, unfortunately also for themselves, very often people modify these conditions to an extent that is dangerous or destructive for the organisms they affect.

2. Artificial Light At Night (ALAN): Benefits or Threat?

Since people learned how to make fire, they began to illuminate the darkness of the night to protect themselves from nearby wild animals, as well as to warm up, cook food, and extend the day. The first source of light was fire but gradually people invented newer and better sources of light, such as torches, candles, oil and gas lamps, and finally in 1879 the electric light bulb appeared on the streets of New York - electric light shone. Thus, people's activity is no longer dependent on the length of the natural day, and we can use artificial light at night (ALAN) in any way to make our lives easier, safer and more comfortable. The first light sources were not very intense, with a yellow-orange color, meaning light with relatively long wavelengths and low energy. Now we know that it was warm light which did not very much disturb function of biological clock, responsible for the circadian organization of physiology and behavior (see later). However, by introducing ALAN into the environment, man has been able to not only improve the quality of his life but also has a profound impact on many (if not all) aspects of life on Earth [1]. From an evolutionary perspective, ALAN is a very young participant in life on Earth, so the organisms living here have not yet developed mechanisms to cope with all the negative effects of its presence. This will be discussed in this article.

In this long history of the relationships between humanity and artificial light, their bright and dark sides can be distinguished. An excellent review by Gaston et al. [2] summarizes the aspects of human life affected by ALAN, highlighting both positive and negative impacts. The following areas are identified: human health and well-being apart from additional time for work and social activity, vehicle accidents, crimes, energy use and carbon dioxide emissions, aesthetics, and ecosystem structure and function. Apparently, almost all of them generate both benefits and threats. The exception seems to be energy consumption and carbon dioxide emissions, which are inextricably linked to the presence of ALAN: when the lights are turned off, energy consumption (electricity) ceases, and carbon dioxide production decreases as well.

It seems obvious that lengthening daylight hours should be beneficial for humans, especially when the length of the natural days is shortened seasonally. However, various limitations have emerged, especially with the introduction of new lighting technologies. In particular, the introduction of energy-saving LED (Light Emitting Diode) lamps emitting cool, white light has paved the way for over-illumination of cities. Moreover, the ever-increasing global urbanization leading to "never-sleeping cities" has become the main cause of the loss of night sky visibility, which is the first described and the best example of light pollution (LP) [3]. In such conditions, another manifestation of LP, i.e. intrusive light, easily occurs. It penetrates our homes, including bedrooms, where darkness at bedtime is essential for healthy sleep (see later).

3. When Does ALAN Become a Source of Light Pollution?

When the artificial light appears in an inappropriate time and wrong quantity it causes an **environmental pollution**, which manifests itself mainly through glare, skyglow, light clutter, light trespass and over-illumination. These effects of night lighting are most visible in cities; therefore, LP and its rapid increase are mainly attributed to urbanization, a global factor of constantly growing scale [3].

It is not easy to distinguish between the use of artificial light to ensure normal human functioning and that which causes LP. It depends primarily on how the light sources are installed, their location, timing of operation, and intensity (see later). Therefore, streetlights seem to be the main cause of light pollution, however it is difficult to make a definitive assessment, even by asking experts. A comparison of LP awareness among "lighting specialists" and "light pollution experts" revealed that even the definition of LP is controversial. For professionals involved in lighting implementation, it was difficult to accept light as a potential environmental pollutant [4]. Fortunately, since then, lighting professionals, and urban lighting designers in particular, have begun to recognize the undesirable side effects of urban lighting and its environmental impact not only on the cities

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themselves but also on the buildings they illuminate and the surrounding areas, and pay attention to the appropriate design of city lights [5].

In a recent paper [6], an average citizens' perception of LP and its impact on various aspects of life has been compared with the opinions of experts (including lighting specialists and scientists). Surprisingly, a significant percentage of study participants were unfamiliar with the concept of LP, indicating a serious lack of awareness of this issue among the general population. Therefore, disseminating knowledge about the dangers of improper use of ALAN seems to be the most urgent need.

Perhaps it would be helpful to address the question to scientists studying the impact of LP on the global biosphere (for review see [7] (pp. 446-447).The first negative effects of ALAN were observed and recorded by astronomers who struggled to continue observing and studying the night sky, even with very advanced instruments – hence the definition of **astronomical light pollution** [8]. Later, biologists began to note the negative impact of the excessive and misused night light on the functioning of ecosystems and human physiology – this is known as **ecological light pollution** [9].

Given the ever-increasing urbanization, it is worth considering another type of light pollution: **urban light pollution**. The use of ALAN in cities is subject to specific regulations, primarily related to traffic safety and crime prevention. Measures to reduce this type of LP will be discussed in the following chapters, but see also [5,10]. Furthermore, urban LP is not only generated by public street lighting, but also by illuminated advertising and digital displays, facade and architectural lighting, commercial and residential indoor lighting that transmits light to the outdoor, and temporary events or decorative illuminations [5,11]. These off-street sources can substantially contribute to local skyglow and horizontal light intrusion and—unlike municipally managed street lighting—are often subject to fragmented, sector-specific, or entirely absent legal controls, complicating mitigation efforts. Satellite and ground-based studies, as well as natural "lights out" experiments, indicate that switching off street lighting only partially reduces total upward radiation. This means that commercial signage, illuminated building facades, and private/residential lighting contribute significantly to this phenomenon, which should be mitigated through targeted policy instruments, planning controls, and voluntary measures [12,13]. Furthermore, attention should be paid to non-human city dwellers, i.e., the various animal and plant species that live there (see next sections).

However, regardless of the LP definition, ALAN is present here and now, and will certainly not only accompany us, but its spread is accelerating. Recently, an increase in the brightness of the global night sky by 9.6% per year has been published [14], while previous estimates predicted it would not exceed 3% per year. It is therefore worth reflecting on the observation made by [15] regarding LP as a new, from an evolutionary perspective, stressor, and its possible impact on the future of organisms that evolved on Earth in stable lighting conditions (L:D 12:12).

4. Adverse Effects of Light Pollution

4.1. Astronomy and Night Sky Observations

The brightening of the night sky, known as sky glow, is one of the most characteristic and bothersome effects of LP. It is created by scattering in the atmosphere of artificial light emitted by various sources, like street and industrial lighting, as well as by private homes. As a result, a distant, visible glow appears over urban and urbanized areas, significantly reducing the contrast between the dark sky and celestial bodies. This, in turn, not only hinders astronomical observations but also negatively impacts the natural environment by disrupting the natural rhythm of light and darkness [16]. This problem is particularly acute for astronomy, as it reduces the number of visible stars and limits the ability to discern the subtle structures of galaxies and nebulae, significantly impairing the image of the cosmos that can be obtained with both the naked eye and telescopes.

The first global picture of light pollution intensity was presented in the World Atlas of Artificial Night Sky Brightness, developed by [17]. This atlas, based on satellite data, demonstrated the global nature of sky brightening, affecting not only large agglomerations but also their suburban and outlying areas. Since then, subsequent editions of the atlas, as well as data from the DMSP-OLS (Defense Meteorological Satellite Program – Operational Linescan System) and VIIRS (Visible Infrared Imaging Radiometer Suite) satellite systems, have enabled the tracking of changes in time and space, demonstrating a steady increase in light pollution intensity worldwide [18].

4.2. Dark Sky Brightening Trends, Causes and Effects – Impact on Observations

European analyses [3] indicate a dominant upward trend in nighttime brightness across the continent, resulting from urbanization, the expansion of road and industrial networks, and increasing building density. At the same time, local decreases in brightness have been recorded in some regions, especially in the countries of the former Soviet Union, Scandinavia, the United Kingdom, Belgium, and northern Germany. The main causes of these decreases are industrial restructuring, including the closure of factories and mines, and the modernization of lighting infrastructure, including the replacement of old luminaires with modern, energy-efficient, downward-facing ones. Another important factor is energy-saving measures, as exemplified by the switching-off of highway lighting in Belgium. Although urban areas still show an increase in light emissions, local implementation of smart lighting systems, such as adaptive LED luminaires, offers the potential to slow down this increase.

Similar trends are observed in Poland, as confirmed by [19] (pp.17-18) prepared by the Light Pollution Think Tank. Satellite observations indicated that night sky brightness in Poland generally increased between 2012 and 2022, although the rate of increase varied by region. The largest increases occurred in the central and southern (industrial) parts of the country, while the darkest areas remained in the east and in mountainous regions. The largest metropolitan areas are the brightest urbanized points in Poland, while in the Bieszczady Mountains the sky only slightly exceeds natural darkness (6-8% brighter). Intensive development of road infrastructure and public space lighting are additional sources of increased light emissions, while the greenhouses are the brightest non-urban spots in Poland.

The brightening of the night sky is increasingly hampering the work of astronomical observatories. This requires constant adaptation to changing conditions and complicates the selection of sites for new astronomical observatories. LP maps and surveys indicate a sustained and spatial increase in ALAN, as well as its spectral and temporal variability [20]. In practice, this means that location criteria – considering both low sky brightness at the zenith, atmospheric stability and sources of LP should move towards multi-criteria assessments using light scattering models and satellite radiance maps [18]. Furthermore, technological changes (e.g., broadband LEDs) and episodic emission sources (mass events, seasonal lighting) can significantly increase sky brightness in a short period of time, even in protected areas, as highlighted by measurements of random events and work on generalizing sky atlases [21]. On a regional scale, initiatives for dark sky protection and the development of astrotourism (e.g. in Poland the Bieszczady Mountains, Suwalki Region) demonstrate a growing interest in maintaining good observation conditions, emphasizing however the need for continuous monitoring and management of lighting order to prevent the degradation of these places [22].

5. Human Health and Wellbeing

5.1. Biological Clock and Its Role in Circadian Organization of Physiology and Behaviour

The regularity of day and night cycles on Earth enables the proper functioning of biological clock, a molecular mechanism ubiquitous in the animal kingdom, which generates changes in biological processes, known as diurnal rhythms [23]. In fact, these rhythms are circadian (from the Latin word meaning "around the day") because these daily fluctuations, regularly recurring each day with values ranging from minimum (nadir) to maximum (peak), oscillate over a period of not exactly, but approximately 24 hours [24]. Crucial is its synchronization with environmental conditions *via* external signals, called *Zeitgeber* (in German "time giver"), in tribute of the German scientist Jürgen

Aschoff (1913–1998). He was one of the founders of chronobiology, a relatively young science that studies the temporal organization of processes occurring in organisms.

The structure and function of the endogenous biological clock are obviously best recognized in humans. A detailed description of its molecular mechanism is beyond the scope of this article, but its overall organization seems worth to be shortly outlined here [25]. It consists of a master clock, a structure located in the brain, and peripheral clocks, present in many, if not all, organs and tissues outside the brain. The molecular mechanisms of the master and peripheral clocks are comparable, but they are synchronized with the environment in quite different ways. The master clock is formed by a pair of hypothalamic nuclei called the suprachiasmatic nuclei (SCN), which are connected directly to the eyes via the retino-hypothalamic tract (RHT). RHT begins in the retina with very specific and relatively recently described photoreceptors [26], the so-called intrinsically photoreceptive retinal ganglion cells (ipRCGs), which contain a photopigment that is not involved in vision. These photoreceptors are particularly sensitive to light waves of 480 nm, or blue light, which in nature corresponds to the sunshine light that announces the end of night (darkness) and the beginning of a new day. At the level of organism, this information shuts down processes typical of nocturnal metabolism and activates those necessary for the light period of the day [27]. This means that light sensed by the ipRCGs informs the SCN about external lighting conditions (thus it is a *Zeitgeber* for master clock), and this information is then transmitted to other body structures *via* neurohormonal pathways. The first "station" of this pathway is the neuroendocrine organ, the pineal gland, which synthesizes the hormone melatonin, known as the hormone of darkness [28]. Melatonin secreted by the pineal gland is immediately released into the bloodstream in a circadian rhythm, peaking during the dark part of the day (at night), while its synthesis in humans is practically negligible during the bright one. The function of melatonin in the body will be discussed in the next chapter.

In addition to the master clock located in the SCN, the human/mammalian clock system also includes peripheral clocks distributed throughout the body's organs and tissues. Their location at a distance from the RHT clearly indicates that light is not a *Zeitgeber* for them. Since numerous peripheral clocks are in the gastro-intestinal system, it seems obvious that food would act as a time-giver for them [29]. This means that the timing, quantity, and composition of meals, as well as the presence of certain specific nutrients, serve as a signal to maintain an appropriate metabolic rate. Therefore, when the natural darkness of night, which for us is usually a time of fasting, is disrupted by the presence of ALAN, we often consume additional meals. This seems to be the simplest explanation for why obesity is so frequently observed in individuals exposed to LP [30,31]. Furthermore, obesity appears to be an epidemic in contemporary societies exposed to LP in "never-sleeping cities". This observation is very clearly confirmed by the results of a longitudinal cohort study of over 100,000 women in the UK, which revealed a highly significant positive correlation between obesity and the presence of light in their bedrooms [32]. Whether participants used light voluntarily or were involuntarily exposed to outdoor (street) lighting that accidentally penetrated their bedrooms, it does not matter, because the result is clearly visible: an adverse effect of ALAN on human metabolism results in the disorder of obesity.

5.2. Melatonin - Message of Darkness and a Potent Antioxidant

Pineal gland-derived melatonin circulates in the blood and reaches every cell and tissue, informing them of darkness (hence its nickname "hormone/molecule of darkness") [28]. while a lack or low blood melatonin level indicates daylight. The level of metabolism must be adjusted to one of these two situations. Blood melatonin level is the only way for humans and vertebrate animals to trigger a behavior and metabolic response appropriate to external lighting conditions. However, it can be disturbed by the appearance of light at an inappropriate moment, i.e., during natural nighttime, because melatonin synthesis in the pineal gland is inhibited by light, especially by short-wavelength blue light [15,33]. This color of light is an important component of the light emitted by cool white LEDs, commonly used in street lighting. This aspect of LP generated by street lighting has already been discussed in the previous chapters.

Blue light is emitted also by the screens of most electronic devices [34,35] used without restrictions, especially by younger generations who cannot imagine life without constantly checking the screens of their smartphones, even in the evening and at night. These light sources generate "**indoor light pollution**," which is even more dangerous because it is created by us when ubiquitous electronic gadgets are applied without proper monitoring. Surveys conducted among high school students in Australia have shown that most of them use electronic devices (smartphones, computers, electronic games) late into the night, resulting in insufficient sleep on weekdays [36]. Of course, this deficiency should be compensated for by extended sleep hours on weekends, sometimes even until noon. Furthermore, staying up very late makes it difficult to wake up for school the next morning, what certainly may lead to poorer academic progress.

Another aspect of the impact of indoor LP on human health was evidenced at the Sleep Disorder Center of the Institute of Psychiatry and Neurology in Warsaw, Poland, where the number of adult patients diagnosed with somnambulism (sleepwalking) has increased very significantly in recent years [37]. Sleepwalking episodes affect up to 15% of children and usually recede around puberty without consequences. Most patients complaining of severe sleepwalking frequently used computers or watched tv at night or shortly before going to sleep, so their initial medical recommendation was to avoid using blue light-emitting devices for at least one hour before bedtime for six weeks. This recommendation proved effective in over 44% of cases, and additional treatment with low-dose SSRIs (Selective Serotonin Reuptake Inhibitors) improved the condition in another 40% of patients. Thus, light emissions from electronic devices before bedtime were a factor that disrupted normal sleep and led to somnambulism episodes in vulnerable patients.

The dramatically increasing use of electronic devices, accompanied by an increase in the incidence of so-called "lifestyle diseases," was likely among the reasons the American Academy of Pediatrics to publish its recommendations that bedrooms must be "screen free zones for children" [38]. Undoubtedly, these recommendations should also be applied to adults and will greatly benefit their health.

Melatonin is not only a hormone of darkness but also a multifunctional molecule with potent antioxidant and free radical scavenging properties [39]. Thanks to its amphiphilic nature (the ability to dissolve in both water and lipids), melatonin readily reaches every organ and tissue, where it can perform functions related to protecting against oxidative stress. Melatonin's antioxidant potential appears to contribute also to its anticancer effects, beyond its direct protection against certain types of cancer [40,41] (see below).

5.3. How Does LP Affect Human Health?

The main effect of ALAN on human health is circadian disruption, i.e., a dysregulation of the biological clock [42]. This manifests itself in two types of desynchronizations: external and internal. **External desynchronization** means that due to the presence of light at an unusual time of day, endogenous circadian system is no longer synchronized with environmental conditions. Consequently, sleep, physical activity, and mealtimes occur at times that do not correspond to the external day/night rhythm, leading to a variety of health problems, primarily due to sleep-wake disturbances. These disorders are further complicated by functional dysregulation of tissues and organs, i.e**. internal desynchronization**. Peripheral clocks within these organs become dysregulated with each other by the appearance of their time-givers at inappropriate times. For example, additional meals consumed at times inconsistent with the production of digestive enzymes, are leading to metabolic disorders. Disturbances in circadian rhythm, especially if they persist for a long time, are often accompanied by already mentioned lifestyle-related diseases, such as insomnia, metabolic syndrome, diabetes type 2, obesity, depression, various types of cancer, and so on [43–45].

As mentioned, ever-increasing urbanization is one of the main causes of LP growth, therefore attention has begun to focus on relationships between the incidence of certain diseases and night sky brightness in various regions or countries. Such studies require collaboration between experts measuring satellite-based night sky brightness and health services focused on monitoring diseases. This is, of course, an activity expensive and time-consuming, as it requires proving a statistically significant relations between LP growth in certain areas and over a specific period (years), and the incidence of certain diseases. Some recently available cohort studies will be shortly presented below.

Long-term exposure to ALAN appears to be detrimental to the health of individuals living in light-polluted areas. The incidence of breast and prostate cancer among the Slovak population between 2003 and 2012 was analyzed in relation to increased nighttime light emissions recorded by satellites [46]). This cumulative LP increase was significantly associated with the incidence of breast cancer, whereas for prostate cancer this association was not significant. The authors concluded that increased LP is a risk factor for breast cancer in Slovakia. However, it seems possible to extend this conclusion to the general situation of ALAN presence, in line with the International Agency for Research on Cancer (IARC) decision regarding night shift work as a risk factor (group 2A) probably carcinogenic to human breast cancer [47]. This type of work requires constant exposure to ALAN, which inhibits melatonin synthesis in the pineal gland. As melatonin is not only a message of darkness but also an antioxidant and oncostatic factor [41], its presence at night protects the organisms against the development of certain types of cancer. When it is missing in the light polluted regions, some types of cancer can develop more easily, what has been shown in the presented research.

Associations between LP measured by satellites and the prevalence of Alzheimer's disease (AD) obtained from Medicare data in the United States (from 2012 to 2018) were assessed recently [48]. Higher AD prevalence was positively associated with higher LP, and this association was stronger than that of alcohol abuse, chronic kidney disease, depression, heart failure, and obesity. It is difficult to draw conclusions about the underlying mechanisms, but sleep disorders associated with the presence of ALAN are always considered as the primary cause.

A recently published research article [49] analyzed the frequency of hospitalizations due to various cardiovascular diseases for over 2 million patients in counties of Eastern Poland (2012 – 2020), in association with LP measured by satellite. The effects of exposure to LP varied depending on the specific cardiovascular disease and were most evident in cases of ischemic stroke and atrial fibrillation. As the area of the studied patient's residence does not belong to the most urbanized and therefore highly light-polluted counties in Poland, further research is worthwhile and recommended.

6. Impact of LP on Ecosystems: Plants and Animals

Apart from human life, anthropogenic LP also affects the functioning of other members of our biosphere. This is particularly evident when ALAN enters the areas primarily occupied by plants and animals, as happens e.g.in forests crossed by highways or railway lines, where the nighttime lighting is never turned off. These areas become inaccessible to the former users, as animals are frequently unable to use the whole space even when underground passages or above-ground bridges are open to species both small and large. Similar unfavorable relationships between ecosystem components and the presence of ALAN are clearly visible in cities, where also trees often support occasional illuminations, such as Christmas lights or light gardens that remain functioning late at night. Each of us has probably seen it personally.

6.1. Effect of LP on Plants

For most of us, plant vegetation is entirely dependent on light for photosynthesis. This is true only partially, because plants also require nighttime darkness for rest, regeneration, and transpiration regulation [50]. Furthermore, plant photoreceptors use light signals as a source of information about day length. Therefore, some plant species, i.e. long day plants flower when the light phase dominates over darkness and vice versa – short day plants whose flowering is inhibited even by short light pulses during the long night because they are perceived as an extension of daylight, which serves as a signal to stop flowering [51].

Day length provides also plants with information about the season, allowing them to prepare for bud growth in spring or to slow down their metabolism and prepare for winter dormancy. However, in light-polluted environments, when plants (e.g. trees) or even parts of them are exposed to ALAN they can develop spring buds too early and therefore they may endanger them to frosty nights in early spring. Whereas in autumn, when the presence of ALAN masks the natural shortening of the day, trees are unable to enter a period of dormancy and senescence, what constitutes threat of uncontrolled exposure to early winter frosts or even snowfall dangerous for branches with leaves that have not fallen in time [52].

6.2. Effect of LP on Animals

Adverse impact of ALAN is much better recognized in animals, and there are numerous scientific articles addressing this issue (e.g. [15], presenting a comprehensive discussion of the effects of LP on vertebrates). Here, we can only briefly summarize this topic and highlight its impact on examples of animal species active during the day or at night.

The influence of ALAN on the physiology and behavior of diurnal birds was recently summarized by [53] based on several million recordings of vocalization duration and its modification by LP (assessed by extraction of mean radiance data recorded by the VIIRS satellite) analyzed in the context of several species' traits, such as eye size, nest type, breeding season, species range, and migratory behavior. Although the summary impact of LP can be evaluated as an extension of vocalization by almost one hour, its significance for the fitness and future of diurnal birds (positive or negative) can only be explained by carrying out of thorough field studies and, most importantly, interregional cooperation.

Presence of ALAN consists also an information for migratory birds flying towards the breeding areas. A mistiming, sometimes extending (usually advancing) up to several days in starting the journey, frequently may resulting in mismatching in the final conditions ensuring breeding success: food availability, nests location, presence of predators etc. [54]. Artificial lighting also significantly interferes with orientation and flight direction of nocturnally migrating birds, which are often trapped by light traps impossible to release from. This ultimately results in death due to metabolic exhaustion [55], many individuals may also die from collisions with illuminated surfaces [56]. A similar fate, due to ALAN, befalls nocturnal insects flying around light sources [57], which we often observe in our gardens, on balconies, and similar places, unaware that we are witnessing a veritable insect hecatomb in the 21st century!

Another very well-known example of the detrimental impact of ALAN on nocturnally active species is the disrupted orientation of sea turtles emerging from eggs laid on ocean beaches [58]. Day-old individuals have very little time to move toward the water and begin their free life. However, artificial lighting often disorients them, making their movements inefficient and energy-wasting, especially since they tend to move toward an artificial light source—in the opposite direction from the water, illuminated by moonlight. It's not difficult to predict the ultimate effect ALAN will have on the future of these species, therefore some societies started to join their efforts to protect "their" turtles against devastating action of LP [59] (see the next section).

One of the most striking examples of nocturnal animals threatened by LP are bats, both large tropical fruit-eating species [60] and small temperate insectivorous ones [61]. Bats begin their flights to foraging sites at dusk, so the presence of ALAN traps them in their roosts, and it is the first step towards the loss of food resources. The complex impact of ALAN on bat behavior and physiology has been discussed in detail by [62]. Subsequently, the possible impact of ALAN-evoked stress on the imbalance between bats and their coexisting RNA viruses, has recently been summarized [63]. Under normal physiological conditions, highly specific immune system allows bats to harbor RNA viruses that are not pathogenic to them and do not cause any signs of inflammation. However, under stress, such as the presence of ALAN combined with other factors at nighttime "wet markets," bats shed their viruses, which can cause disease in many other animal species even on a large scale [64].

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6.3. Effect of LP on Pollinators

Last, but not least, the impact of LP on ecosystems also concerns the significant decline in effective plant pollination, responsible for more than 75% of all harvested crops [65,66]. Pollinator activity also has a significant impact on maintaining biodiversity and supporting ecological networks through the reproduction of wild plants, plant-animal interactions, and many other ecosystem services, such as climate regulation or seed dispersal, most evident in the regeneration of tropical forests [66]. Pollinators include numerous species of insects, birds, and bats, and recent decades have been associated with a very significant and continuous decline in their number and diversity, one of the most important causes of which seems to be increasing LP. All pollinator species have their own circadian rhythm of activity: diurnal or nocturnal, and any disruption in night length can negatively impact the frequency of their visits to plants [67]. Furthermore, the synchronization of plant flowering with pollinator activity is crucial, and this can be interrupted due to the differential impact of LP on individual components of this interspecific cooperation, which can be best illustrated by the reduced regeneration of tropical forests whose seeds are dispersed by fruit bats [68].

7. Legal Status of Light Pollution

Accepting excessive/inappropriate nighttime lighting as a pollutant hazardous to both humans and ecosystems requires the development of regulations to protect against this threat. It is unimaginable to adopt a single global legal system applicable in every country, even though light knows no borders. In-depth analysis of the legal situation in Europe and beyond can be found in Yakushina's recent article [69], which divides regulations into two interrelated types: law and policy. Policy can be considered a broad set of guidelines that constitute a framework for law, and therefore has less enforcement power, is more flexible than legal documents, and can therefore be modified without legislative procedures. Regulations addressing LP are found in both policies and legal standards, primarily because these are still in the early stages of their development. Policy-based approaches are particularly dominant, aiming to define night light as pollution, identify its sources, and support measures to reduce ALAN and mitigate its effects. Individual countries are introducing regulations with varying levels of stringency, and it appears that it will be some time before dark sky protection becomes a universal requirement. But we have to start somewhere.

7.1. Legal Regulations in Europe

Various legal measures are being taken across Europe to reduce LP, but their scope, level of detail, and effectiveness vary significantly between countries.

The regulations introduced in Spain in 2001 can be considered a European pioneer in the field of dark sky protection [70]. They limited the height of lighting masts/poles, as well as the color and intensity of light, which proved particularly beneficial for the Island of La Palma, home to some of the most important astronomical observatories in Europe. These regulations not only ensured the maintenance of high-quality scientific research but also laid the foundation for the development of local astrotourism, which is now a significant sector of the region's economy.

But Slovenia was the first European country to introduce in 2007 statutory regulations regarding a requirement for luminaires with full up-cut and color temperature limitations. These measures not only reduced energy consumption by approximately 20% over five years but also improved night sky visibility, a significant benefit for both local scientific institutions and tourism initiatives [71].

France opted for more stringent solutions in 2018, introducing a requirement to turn off illuminated advertising and public building lighting between 1:00 a.m. and 6:00 a.m. These regulations reduced energy consumption in the advertising sector by nearly 30%, demonstrating that even relatively simple measures can provide tangible environmental and economic benefits [5].

Another example is the regional regulations in force in the Aosta Valley, Italy [72]. Since 2009, dark sky zones have been established around national parks, reducing scattered light emissions by

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approximately 25%. As a result, both the natural environment and nighttime astronomical observations have benefited, thanks to improved conditions.

7.2. Dark Sky Protection in Poland

Compared to the above examples, the situation in Poland looks rather poor. There are no nationwide regulations directly addressing the problem of LP. Current Environmental Protection Law and Construction Law only address this problem indirectly, without setting precise limits or standards for light emission. Measures aimed at reducing excessive emissions are undertaken primarily at the local level, through municipal or community initiatives, but their scale is limited, and they do not create a coherent system to counteract increasing light pollution [19](pp.26-29).

Across the world, alongside government measures, grassroots and community initiatives are becoming increasingly important. A good example from Poland is Sopotnia Wielka in the Beskid Mountains, which, thanks to the cooperation of residents, NGOs, and experts, has achieved the status of an International Dark Sky Community [73].

Another example of the important role of NGOs in promoting the protection of the night sky is the activity of the International Dark-Sky Association (IDA) which runs a program to certify areas that meet stringent dark-sky protection standards. Numerous reserves in the United States, Canada, and Europe now hold the status of International Dark-Sky Parks, which not only provides conditions for scientific research but also protects biodiversity and the natural rhythms of wildlife [74].

Effective protection of the nightscape, however, requires a combination of legislative, technological, and social measures. Examples from the European countries presented here demonstrate that consistently implemented regulations produce tangible results. Moreover, grassroots initiatives, such as those in Poland and many other countries, demonstrate that local communities can also play a significant role in counteracting LP.

8. Options for Reducing/Mitigation Light Pollution

Light pollution, defined by the International Commission on Illumination (CIE) as "the sum of all negative effects of artificial lighting," has become a global environmental problem in recent decades. Its consequences extend far beyond the aesthetics of the night landscape and hinder astronomical observations, as they include the destruction of ecosystems, negative impacts on human health, energy waste, and the loss of the cultural and scientific heritage of the night sky [75]. Effective mitigation of this phenomenon requires a comprehensive approach combining technological innovation, spatial planning, economic instruments, and active social engagement.

The basis for technical solutions is the proper design and modernization of lighting infrastructure. The use of ULOR 0 (Upward Light Output Ratio) luminaires significantly reduce skyglow and glare, which are bothersome to both humans and animals [76]. Equally important is the choice of light color – sources with a high color temperature (above 4000 K) emit a lot of blue radiation, which is strongly scattered in the atmosphere and disrupts the circadian rhythms of organisms. Therefore, international recommendations indicate the need for warm light colors, not exceeding 3000 K, and optimally in the range of 2200–2700 K [74]. In recent years, narrowband amber (NBA) and phosphor amber (PCA) LEDs have become increasingly popular, emitting minimal amounts of shortwave blue light while ensuring high energy efficiency [75]. Lighting control systems provide additional protection against LP. The use of motion sensors, dimmers, and automatic lighting schedules allows for the adjustment of lighting intensity to current user activity and the time of night. Such intelligent systems reduce unnecessary light emissions and energy consumption, additionally limiting greenhouse gas emissions [77].

However, reducing LP cannot rely solely on technology – spatial planning is equally important. Many countries employ a zoning model in which areas of greatest natural or astronomical value are subject to the strictest lighting standards. Transitional and buffer zones are gradually being subjected to less stringent regulations. Such solutions, implemented in areas such as dark sky reserves, effectively protect natural night conditions and support the development of astrotourism [78].

Urban areas are also increasingly implementing "dark infrastructure" solutions, i.e. networks of corridors with limited lighting enabling the migration of nocturnal species and counteracting habitat fragmentation. Good examples of effective planning regulations include the Sky Law in the Canary Islands, and the Mackenzie District Lighting Ordinance in New Zealand, both in force since 1981 [79].

In recent years, LP reduction policies have increasingly introduced methods based on economic and ecological analysis of the value of the night environment. Research shows that excessive artificial lighting leads to measurable economic losses resulting from the decreased ecosystem services, such as the regulation of biological processes, pollination, and the quality of natural habitats. Integrating this perspective with investment and spatial planning—using tools such as the Natural Capital Accounting (NCA)—allows for better consideration of the environmental costs of excessive lighting. This approach promotes the formulation of effective public policies and sustainable development strategies that view LP reduction as not only an environmental factor but also an economic one [80].

From a public health perspective, reducing light emissions at night brings tangible benefits. Numerous studies confirm that excessive exposure to ALAN disrupts circadian rhythms, reduces melatonin secretion, worsens sleep quality, and increases the risk of chronic diseases such as depression, obesity, type 2 diabetes, and cancer [81]. Improving the quality of outdoor and indoor lighting can mitigate these negative impacts, contributing to improved human well-being and reducing the burden on healthcare systems. Reducing night-time light emissions also has a positive impact on biodiversity, restoring natural conditions for pollinating insects, birds, and bats, whose activity and migration are highly dependent on natural darkness [78].

According to research presented by [79], local community involvement is one of the most effective factors in long-term LP reduction. The authors emphasize that resident participation not only increases acceptance of new solutions but also strengthens local sustainability: when a community understands the environmental and health benefits, it is easier to maintain high lighting standards in the long term. Also, local education and astrotourism can become drivers of regional economic development, combining environmental protection with local prosperity. Moreover, responsible lighting is not only a matter of nature conservation but also of quality of life and human heritage. Well-designed and implemented lighting systems deliver immediate benefits by improving safety, supporting biodiversity and human health, and creating more welcoming urban spaces. Moreover, preserving dark skies is an integral part of sustainable development and cultural heritage, just as much as protecting clean water and air [79].

A new challenge for the protection of dark skies has become the problem of light emission from Earth orbit in the context of space law, as described by [82]. The author notes that the increase in the number of commercial satellite constellations requires updating existing international treaties to include the protection of the night sky as a common good of humanity. In her analysis, the right to "dark sky" is equated with the right to an unpolluted environment, opening new perspectives for space policy and the sustainable management of orbital space.

9. Summary (Table 1) and Conclusions

Light pollution (LP), a significant component of Earth's global anthropogenic pollution, is only slowly reaching public awareness, as we have attempted to highlight in this review article. As can be seen, the number of specific observations or local measurements is steadily increasing and has recently been supported by some cohort studies combined with satellite registrations of night sky brightness. These highly desirable initiatives provide scientists with a powerful tool that can readily demonstrate how LP is increasing and how it is related to harmful effects on various aspects of life on Earth, from the extended duration of bird songs to the incidence of certain cancers in humans. It is difficult to deny the results of measurements covering millions of participants and an even larger number of satellite observations, so all hope lies in the new, younger generations for whom such arguments may be valid.

Regardless of the astronomical and ecological LP, not readily acknowledged by society at large, we would like to draw readers' attention to the relatively recently proposed concept of "indoor light pollution." It is generated by people in their own homes, primarily (though not exclusively) young users of electronic devices, and is detrimental to their circadian rhythms and overall body function. This is especially true given that we are currently unable to predict the possible long-term effects of these disturbances, relatively recently generated, on the sustainability of the circadian regulatory system, which is as old as life on our planet. While the mitigation of outdoor LP in various locations requires some investment and effort of local communities, reducing artificial LP indoors is relatively easy and cost-free: simply turning off devices that consume electricity and emit light.

Therefore, our conclusions are twofold:

1st - People must recognize that light pollution exists and inappropriate use of artificial light at night is dangerous both to themselves and to other inhabitants of the Earth.

2nd - When artificial light at night is limited, life on our planet will be healthier and, additionally, less expensive.

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