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Systematic Review

A Systematic Review for Establishing Relevant Environmental Parameters for Urban Lighting: Translating Research into Practice

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Abstract: The application of lighting technologies developed in the 20th century has increased the brightness and changed the spectral composition of nocturnal night-time habitats and night skies across urban, peri-urban, rural, and pristine landscapes, and subsequently, researchers have observed the disturbance of biological rhythms of flora and fauna. To reduce these impacts, it is essential to translate relevant knowledge about the potential adverse effects of artificial light at night (ALAN) from research into applicable urban lighting practice. Therefore, the aim of this paper is to identify and report, via a systematic review, the effects of exposure to different physical properties of artificial light sources on various organism groups, including plants, arthropods, insects, spiders, fish, amphibians, reptiles, birds, and non-human mammals (including bats, rodents, and primates). PRISMA 2020 guidelines were used to identify a total of 1417 studies from Web of Science and PubMed. In 216 studies, diverse behavioral and physiological responses were observed across taxa when organisms were exposed to ALAN. The studies showed that the responses were dependent on high illuminance levels, duration of light exposure, and unnatural color spectra at night and also highlighted where research gaps remain in the domains of ALAN research and urban lighting practice. To avoid misinterpretation, and to define a common language, key terminologies and definitions connected to natural and artificial light have been provided. Furthermore, the adverse impacts of ALAN urgently need to be better researched, understood, and managed for the development of future lighting guidelines and standards to optimize sustainable design applications that preserve night-time environment(s) and their inhabiting flora and fauna.

Keywords: artificial light at night (ALAN); biological rhythms; ecological light pollution; exterior illumination; light pollution; light-emitting diodes (LEDs); sustainable lighting; urban lighting; urban lighting practice (ULP); urban lighting research; systematic review; polarized light pollution

1. Introduction

From the 20th century onward, cities and towns around the globe have applied artificial lighting technologies at night. This human-centric widespread illumination of the nightscapes has been implemented to provide a sense of safety and security [1,2], to showcase the historical and architectural significance of past and present times [3], to enable a 24/7 lifestyle, and to boost the economy [4,5] and tourism [6]. Traffic and pedestrian routes, as well as buildings and landscape elements, have often been brightly and colorfully illuminated by artificial light at night (ALAN) not only for visibility but also to provide lit networks and infrastructures so individual users and society can function efficiently at night (Figure 1).

Figure 1. A schematic diagram that illustrates the extent of artificial lighting in four different scenarios: urban, peri-urban, rural, and natural landscapes. (**a**) Architectural lighting in urban areas illuminates buildings, façades, architectural structures, and monuments. In some scenarios, it is accompanied by commercial and retail advertisements in the form of backlit panels, self-illuminated sources, and decorative lighting for non-permanent events. (**b**) Pole-mounted luminaires and bollards provide visibility for pedestrian and cycling paths at night for public amenity areas and neighboring urban zones, such as parks. (**c**) Street lighting is used for the safe passage of pedestrians and cyclists and to also assist in visibility for vehicular circulation at night. (**d**) In natural environments, lighting on roads and motorways aids vehicular travel. In addition, stopover locations, such as gas and train stations, as well as villages with rural houses, become illuminated spots at night. Source: Authors' figure.

In recent decades, ALAN has extended in scale and form [7], causing the unintentional anthropogenic stressor known as light pollution (LP), which can occur both as astronomical light pollution [8] and ecological light pollution [9]. Unshielded luminaires and improperly managed lighting can radiate light toward the sky, where it scatters within the atmosphere, creating a diffuse glow called skyglow [10]. Skyglow is detrimental to the night sky, and it often extends into dark habitats that have natural day–night light cycles [8]. Typically, artificial skyglow is relatively dim (0.001–0.1 lx) [10] but peak skyglow levels can be brighter than the full moon [10,11]. A recent skyglow model suggests that about 80% of the world's population now lives under light-polluted skies [12] and there is an increase in LP of more than 2% per year [13,14], which poses a serious threat to biodiversity and human health [15–20]. ALAN can also suppress melatonin, known as the night hormone, in various vertebrate species even at skyglow-like low light levels (0.01–0.03 lx) [11,21]. This may inhibit crucial day- and night-time cycles because 30% of all vertebrates, and more than 60% of all invertebrates, have visual systems adapted to (low) natural nocturnal light levels (i.e., moonlight maximum at ca. 0.3 lx and starlight at ca. 0.001 lx) [11,15].

The concept of LP and ALAN as an anthropogenic pollutant that unintentionally causes the "loss of night" (Figure 2) is relatively new to urban lighting practice (ULP). For most lighting professionals, which includes architectural lighting designers (ALDs), urban lighting designers (ULDs), and electrical illuminating engineers, ALAN is considered a technological tool that drives their field of study rather than an element that can have adverse effects upon the surrounding environment (i.e., the night sky, flora, and fauna), resulting in negative effects that have a local and global impact [22]. Improperly managed ALAN may extend to areas where it is not intended and needed. With this in mind, the current urban lighting practice lacks a foundation on ecology, astronomy, and environmental science to address matters related to minimizing this issue.

Figure 2. Overview of the unintended consequences of improperly managed lighting in the form of LP. (**a**) Images of the Earth at night from the International Space Station (ISS). (**b**) The density of light emissions from cities causes skyglow, which prevents the visibility of stars. (**c**–**h**) The source of LP and obstructive light from artificial light is commonly located in urban areas with (**c**–**d**) the illumination of landmarks, buildings, and monuments, (**i**–**m**) the illumination of gateways and bridges, and (**h**) self-luminous advertisement screens. (**h**,**j**) Some applications can potentially over-illuminate an area and cause light trespass/spill light beyond the intended function. (**f**,**h**,**k**,**l**) The improper management and application of artificial lighting technologies may even extend toward natural environments, spilling light into (**r**–**v**) land, (**i**–**m**,**p**,**q**) waterbodies, and (**e**–**h**,**n**–**p**,**r**,**s**) the sky and, in consequence, adversely affect (**n**,**o**,**q**,**s**,**t**,**v**) ecosystem services and living organisms. (**f**,**h**,**k**,**l**) For instance, the improper application of artificial lighting may over-illuminate the sky when luminaires emit light toward the sky. (**i**–**m**,**p**) Other artificial lighting applications, such as illuminated river bridges, may over-illuminate the nearest waterbody and potentially shift its optical composition at night. Image sources: (**a**) NASA/Unsplash, (**b**) Johams Leguisamo, (**c**) Suhyeon Choi/Unsplash, (**d**) Lynn Friedman/Flickr (CC BY-NC-ND 2.0), (**e**) Daniel Jolivet/Flickr (CC BY 2.0), (**f**) Mihaly Koles/Unsplash, (**g**) Dylan LaPierre/Unsplash, (**h**) Andrea Leopardi/Unsplash, (**i**) Jamie McGlinchey/Unsplash, (**j**) Charles Koh/Unsplash, (**k**) Bill Xi/Unsplash, (**l**) Cees Van Wageningen/Unsplash, (**m**) Jason Polychronopulos/Unsplash, (**n**) Potyo Imre/Flickr (CC BY 2.0), (**o**) Potyo Imre/Flickr (CC BY 2.0), (**p**) Hans Permana (CC BY-NC 2.0), (**q**) Paul Vecsei, (**r**) Luca Fontanarosa/Unsplash, (**s**) Tine Ivanic/Unsplash, (**t**) Zdenek Machacek/Unsplash, (**u**) Bradleypjohnson (CC BY 2.0), and (**v**) Valeria Moschella.

ALAN researchers have built an extensive body of empirical evidence across taxa that identifies potential negative behavioral and physiological responses induced by ALAN [23–25]. For instance, studies on terrestrial organisms, such as bats [23], birds [24], and insects [25–27], as well as micro-organisms and aquatic species [28–30], have revealed changes in their behavior and physiology when their habitat (aerial, aquatic, or terrestrial) is exposed to ALAN. Various studies have investigated ALAN to question the current habit of over-illuminating nightscapes and encourage the re-evaluation of night-time illumination. This is based on research-informed design in order to introduce knowledge on ecology and to implement environmental values in the practice of urban lighting [31–33].

However, while ALAN researchers report the ecological consequences of ALAN to their peers, with some efforts to propose the need for environmental conservation measures, less focus has been given to efficiently translate ecological knowledge toward lighting practitioners and the industry. Consequently, the insights obtained by ALAN researchers seldom reach the lighting professionals who are involved in the application of lighting technologies. This is a problem because for the lighting community it is difficult to evaluate the relevance of biological studies. It is also challenging to interpret the results in the context of ULP without clear guidance, all of which can hinder the planning and designing of lighting schemes to provide visibility, safety, and security while also minimizing the adverse impact on the natural environment.

To reduce these impacts, it is essential to translate relevant knowledge on the adverse effects of ALAN into applicable ULP. Therefore, the aim of this paper is to identify and report, via a systematic review, the effects of exposure to different physical properties of ALAN on various organism groups, targeting mainly lighting professionals and research gaps.

This work should also motivate research-informed ULP by raising awareness about the impact of ALAN on the night-time environment. It is not only lighting professionals who will gain from this research review; those involved in the design, planning, and approval process will also benefit. This includes architects, urban planners, landscape designers, sustainability consultants, and planning officers (representatives of local planning authorities) [22].

This article is organized into the following sections: Section 2 provides an overview of concepts and terminologies and the physical parameters of ALAN considered by ULP and ALAN research as tools required to properly translate the existing knowledge and ensure better communication between ULP and ALAN research. Section 3 defines the scientific questions. Section 4 demonstrates the procedure performed for the systematic review based on PRISMA 2020 guidelines. Section 5 provides the results of the systematic review. Section 6 includes the limitations of the study. Section 7 discusses the research findings and their implications. Section 8 presents the conclusions of the review; it also provides a synthesis of the key points and recommends new areas for future urban lighting research. Appendix A includes terminologies and definitions related to artificial lighting applications. The supplement includes additional detailed content relevant to the results of Section 5.

2. ALAN Lingua Franca

2.1. Concepts and Terminologies

The key terms on the urban night-time environment and the presence of light were developed by the field of lighting/technology (ULP) and the field of astronomy/ecology/environmental sciences (ALAN research). Each domain shares an interest in light and darkness; however, each field independently develops terminologies [22,31,34–36]. The domain of ULP combines the knowledge of human vision (during the day) with applied lighting technologies in the built environment, which forms a practice focused on the application of brightness, contrast, and colors that mimic typical day-time conditions. However, too often, these solutions unintentionally neglect the negative consequences of added artificial light on natural nocturnal environments and ecosystems. The ULP still relies on terms for the application of ALAN based on human vision that mimics typical day-time conditions for cities and towns at night. In contrast, the domain of ALAN research already involves scientists from varied fields [22,34], which results in a heterogeneous vocabulary and the use of non-SI units (units that are not defined as part of the International System of Units) for nocturnal light, making it sometimes difficult for members outside of these domains to follow.

ALAN research acknowledges lunar cycles and starlight, the interaction of ALAN and natural nocturnal light with environmental conditions (e.g., cloud cover or snow [37,38]) as important, and it recognizes ALAN as a potential anthropogenic pollutant. This means that in order to consider sustainable objectives [39], a collaborative framework between ULP and ALAN research is needed to potentially establish a common ground. A mutual understanding between domains can clarify terminologies to carefully communicate and efficiently transfer scientific research on the night-time environment and the lighting approaches used in the practice to assess solution-oriented systematic learning [40–42].

For further reading on the terminologies and definitions addressed by both domains, see Table 1 and Appendixes A1–A5.

Table 1. Summary of tables on terminologies and definitions related to ALAN research and ULP (see Appendix A).

Table No.	Description
A1	Overview of terminologies and definitions of natural and artificial light sources relevant for ALAN research and ULP
A2	Overview of terminologies and definitions of responses to light in living organisms and ecosystems
A3	Overview of various types of electric light sources commonly used in urban settings in the past and the present
A4	Overview of radiometric and photometric quantities of light and units
A5	Overview of terminologies and definitions of ALAN as a pollutant

2.2. Physical Properties of Artificial Lighting Considered by ULP and ALAN Research Domains

ULP domains usually rely upon a commonly developed technical language of lighting to deliver illuminated settings based on the spectral sensitivity of human day-time vision [43–45]. For many years, the practice of lighting has treated the night as a blank canvas to showcase historic, architectural, cultural, economic, technological, and societal legacies of cities that needed to be not only visible during the day but also illuminated at night as a reminder of society's achievements, without performing environmental impact assessment studies. Some practitioners are advocating for a change in this approach [31]. The current lighting practice often disregards lighting approaches focused on reducing the amount of implemented light as it lacks foundations on how the applied light might become an anthropogenic pollutant and how light is perceived by other organisms (e.g., low light intensities from natural light sources and environmental conditions [37,46,47].

In contrast, ALAN research provides a broad understanding of light as a potential artificial pollutant in need of careful management [7,10,48]. The presented detailed results of studies address physical parameters of light (e.g., ultraviolet and infrared radiation) that are typically considered as parameters hardly detected by humans [49] and have been shown to be used as a source of information by many other organisms [50–52].

To ease the communication between these two domains and to understand the difference in commonly used units and symbols of different physical quantities of artificial light, Table 2 is elaborated based on discussions of representatives from these two domains. In short, one can distinguish mainly between radiometric and photometric quantities (the photometric spectral band that matches human day-time responsivity) and units as well as measurement geometries. Irradiance is the radiometric quantity for light incident on a surface per unit time and has illuminance as the photometric counterpart. Biologists sometimes report radiometric quantities [50–54] in a spectral band relevant for photosynthesis called photosynthetically active radiation (PAR) [20,54]. Radiance is the light emitted from or incident on a surface per unit time within a specific solid angle and has luminance as the photometric counterpart, sometimes casually called "brightness". The night sky radiance (also often called "night sky brightness") is often reported in astronomical units of magnitudes that are confusing for non-astronomers as they are a negative logarithmic scale, recently used also in ALAN research due to the common use of small sky radiometers called "sky quality meters" (see Hänel et al. [21] for an introduction on night sky brightness). Radiant flux is the light per unit time with the photopic counterpart of luminous flux, often given with luminaires. Spectral properties are becoming more and more important recently, and there is a shift from correlated color temperature (CCT) to spectral power distribution (SPD), given a wavelength-resolved physical quantity of light (e.g., spectral irradiance), which would enable the use of new methods, such as the spectral G-index or similar indices (please note that the G-index is not yet evaluated or adopted by a standards development organization but recommended in some regulations already) [53]. Other properties of light that are not widely characterized yet but are becoming more and more important are, for example, flicker in ULP and the degree of polarization in ALAN research.

Table 2. Overview of usage of physical quantities of artificial light by each domain. "*" The photosynthetically active radiation (PAR) originates from horticulture but is also used widely in biology (e.g., for primary production of phytoplankton). Irradiance is then substituted with photosynthetically active photon flux density (PPFD) and radiant flux with photosynthetically active photon flux (PPF); "**" sky radiance is reported in astronomical magnitudes from star brightness, used in ALAN research with small night sky radiometers, like the sky quality meter (SQM).

Physical Quantity	Domains	
	ULP	**ALAN Research**
Irradiance, E_e (W/m^2)	rare	common
Illuminance, E_v (lx)	common	rare
PAR * photon flux density (PPFD) E_{PAR} (μmol photons/m^2)	not used	rare
Radiance, Le ($W/m^2 \cdot sr$)	not used	rare
Luminance, Lv (cd/m^2)	common	not used
Sky radiance (astronomy) ** $L_{sky,SQM}$ (mags/$arcsec^2$)	not used	rare
Radiant flux, Φ_e (W)	not used	rare
Luminous flux, Φ_v (lm)	common	rare
PAR* photon flux (PPF) Φ_{PAR} (μmol photons/s)	not used	rare
Spectral power distribution (SPD; e.g., spectral irradiance in $W/m^2 \cdot nm$)	rare (increasing)	rare (increasing)
Correlated color temperature (CCT; K)	common	rare
Color rendering index (CRI; R_a)	common	not used
Flicker frequency (Hz)	rare (increasing)	not used
Flicker %	rare (increasing)	not used
(Degree of) Polarization	not used	just emerging

3. Scientific Question

To accomplish the research goal of establishing relevant environmental parameters for urban lighting and to identify the properties of artificial light, which are considered to be profoundly detrimental to natural day- and night-time cycles of flora and fauna, the following questions have been posed:

Question 1. *What are the most relevant parameters of artificial lighting for evaluating impacts on different organism groups that should be used by ALAN researchers in their research studies and by lighting professionals in their day-to-day practice in order to minimize the negative effects without having to turn off lighting?*

Question 2. *How do we translate ALAN research for lighting practice to address environmental concerns?*

4. Materials and Methods

This section presents the scoped literature procedure via a systematic review and synthesis criteria, which involved the findings of research studies that demonstrated ALAN as a potential stressor to the behavior, physiology, or survival of selected organism groups. The review follows PRISMA 2020 guidelines (Figure 3) [55–58]. First, categories of organism groups were arranged to develop keyword combinations for literature search. Only English keywords were chosen. The summary of keywords is presented in Table 3.

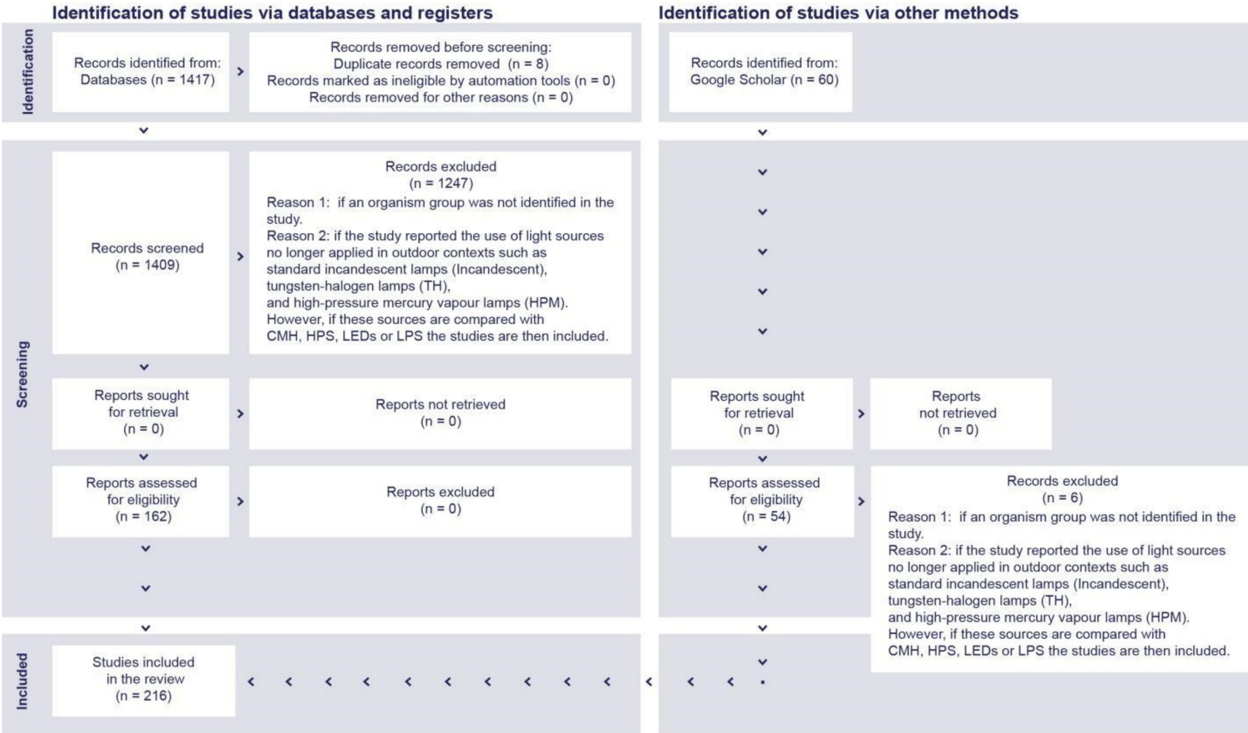


Figure 3. Flow chart depicting the selected studies according to the preferred reporting items for systematic reviews (PRISMA 2020). Declaration and the exclusion criteria presented in Section 4.

In the group of arthropods, three separate searches were performed: one for arthropods, one for insects, and one for spiders. In the group of non-human mammals, four separate searches were performed: one for mammals, one for ungulates, one for primates, and one for rodents. The keywords were searched for in titles, abstracts, and the keyword section. "AND" is used to bind keywords (e.g., artificial light with an organism group) and "*" to broaden the search finding by including word stems or plural forms of the keywords.

All review article types were excluded. The searches were aimed to identify only peer-reviewed articles in the English language. The literature searches were performed in January 2020, and the abstracts were subsequently reviewed (from March to June 2020). The literature searches were performed via an electronic database search in Web of Science and PubMed. The content in titles and abstracts was scanned to identify physical properties of artificial light linked to a change or no response in the determined selected organism groups.

Table 3. Search strategy: Summary of keywords used for selected organism groups.

Category of Organism Groups	Keyword #1		Keyword #2		Keyword #3		Keyword #4		Keyword #5
Plants	"artificial + light"	AND	plant *	-	-	-	-	-	-
Arthropods	"artificial + light"	AND	arthropod *	OR	insect *	OR	spider *	-	-
Fish	"artificial + light"	AND	fish *	-	-	-	-	-	-
Amphibians	"artificial + light"	AND	amphibian *	-	-	-	-	-	-
Reptiles	"artificial + light"	AND	reptile *	-	-	-	-	-	-
Birds	"artificial + light"	AND	bird *	-	-	-	-	-	-
Non-human mammals	"artificial + light"	AND	mammal *	OR	ungulate *	OR	primate *	OR	rodent *

To minimize bias, the data from the studies included in the systematic review were extracted in two categories: (a) one that identified key indicators of artificial light properties (see Table 2 and Figure 3) and (b) one that identified key findings in the study reports in an organism group when exposed to artificial lighting properties. Table 2 shows the physical properties of artificial lighting with the corresponding symbol and unit used for the systematic review. Figure 3 shows an overview of artificial light sources included in the systematic review. Exclusion criteria were applied to the records in the case any of the following elements were present:

- Organism group was not identified.
- There was day-time exposure to artificial light.
- Horticultural studies were performed to enhance plant growth.
- Phased-out light sources were still often used for outdoor illumination, including incandescent lamps (Incandescent), tungsten-halogen lamps (THs), and high-pressure mercury vapor lamps (HPMs).
- Illuminance > 200 lx, as a maximal threshold to represent typical light-polluted scenarios in outdoor environments.
- Studies were conducted addressing the impact of ALAN on humans.

These criteria were designed to present a review on the properties of artificial lighting that shape typical applied artificial light by lighting professionals creating light-polluted scenarios. In addition, the intent was to reconcile an understanding of ecology with a commitment to sustainable demands relevant to the application of lighting technologies at night and for those in charge of managing lighting scenarios.

The titled and abstracts of records were screened, and then the full texts of studies were reviewed to identify, order, and aggregate the results as follows: (a) an organism group defined as the main study subject, (b) the reported light source used, (c) the reported physical properties of artificial lighting, and (d) a response, multiple responses, or no response to ALAN. Six researchers participated in the screening assessment of Table 2 and Figures 4–9. One researcher performed a double screening of the studies to properly identify the results and to assess the content in Figures 4–9 and the Supplementary Materials. Two researchers performed an additional screening of the studies to properly translate the results taken into account for Figures 4–9 and for the Supplementary Materials. Three researchers screened and assessed the appropriateness of the summarized content for Figures 4–9. A final screen was performed by all researchers for Figures 4–9.

Category of organism groups		Research Databases: Web of Science	Research Databases: PubMed	Additional articles	Total of studies per category
		13	1	5	19
	Uncat.	6	4	9	43
	Insects	21	1		
	Spiders	2	0		
	Total	29	5		
		20	0	8	28
		8	0	4	12
		4	0	4	8
		62	2	12	76
	Uncat.	7	0	12	30
	Primates	2	1		
	Ungulates	0	0		
	Rodents	7	1		
	Total	16	2		
Total of included studies					216

Plants | Arthropods, Insects, and Spiders | Fish | Amphibians | Reptiles | Birds | Mammals (non humans)

Figure 4. Summary of reported studies that investigated the impact of ALAN in organism groups. A total of 216 studies were included in the systematic review. The subcategory of "Uncat." indicates all studies that were searched using the main category of the group as a keyword.

Once the studies were arranged by organism groups, the reported studies were screened to identify the light source type that was investigated in each study. Some studies did not report the type of artificial light source and instead, described the physical properties of artificial light. For this reason, if a non-identified artificial light source was presented in the included studies, the non-identified artificial light source was addressed as ALAN. ALAN was then categorized as direct ALAN (e.g., if described as a point source) or indirect ALAN (e.g., if described as skyglow).

Figure 4 presents an overview of the total number of studies included per electronic database search; the number of studies in additional articles that were included; the total number of studies included, which are categorized by organism groups; and the total amount of studies reported for the systematic review. A double screening of the studies was assessed by one researcher.

5. Results

5.1. Impact of Artificial Lighting on Organism Groups

A total of 216 studies were identified. These studies included behavioral and physiological responses in plants [59–77]; arthropods, including insects and spiders [71,78–119]; fish [120–147]; amphibians [148–159]; reptiles [160–167]; birds [168–243]; and non-human mammals, including bats, primates, rodents, and marsupials [24,160,161,174,244–269], when their habitats, aquatic or terrestrial, were artificially illuminated with direct or indirect emissions of ALAN (i.e., all light sources of artificial light). The results of our systematic review show that the most studied organism groups exposed to night-time illumination were birds (76 studies); arthropods, insects and spiders (43 studies); non-human mammals, including bats, primates, rodents, and marsupials (30 studies); fish (28 studies); plants (19 studies); amphibians (12 studies); and reptiles (8 studies). A total of 4 studies are doubled marked as these present results for more than one group (e.g., results for birds and mammals) [71,160,161,164].

5.1.1. Plants

In general, it appears from the 19 plant studies that growth is stimulated to increase foliage [59], stems [60], density, and cover [61,62] when the oscillations of natural day and night cycles are less clear and nights are lighter due to ALAN. In addition, ALAN was shown as a disruptor of processes that can even affect interactions between plants and other organisms. For instance, plants exposed to ALAN demonstrated an earlier initiation of budburst [63], an early and increased flowering process [60,64,65], a delayed flowering state [66], altered plant–herbivore interactions [67,68], altered leaf litter decomposition [69,70], and disrupted pollen transport [68].

5.1.2. Arthropods: Insects and Spiders

The 43 arthropod studies showed clear ALAN-mediated behavioral responses (mainly attraction or avoidance) and physiological responses (e.g., gene expression, growth, and fecundity). Light is considered an essential cue for this organism group at night. Therefore, if ALAN is present at the wrong time and place, it can disturb orientation, navigation, finding resources, foraging, courtship, reproductive behavior, interaction between species, and predator avoidance, which can lead to changes in population dynamics and community structure.

The majority of studies reported a positive phototactic response, i.e., the attraction of organisms toward a stimulus of light, for example, when exposed to the emission of light or when proximate to illuminated locations, varied types of light sources, or polarized light pollution at night.

For instance, spiders [78,79], female and large-sized non-biting midges, which include *Chironomus plumosus* and *Procladius* sp.; the small-sized midges *Tanypus punctipennis* [80]; moths [81–84]; and camel spiders, were observed moving toward illuminated locations that presented higher densities of prey at night. A total of four studies reported aquatic and terrestrial arthropods, insects, and spiders that commonly move between aquatic and terrestrial landscapes as attracted to illuminated settings located nearby [78,85–87]. A total of seven studies compared varied types of light sources that may trigger attraction in arthropods [88–95]. Three of the five studies compared the attraction of arthropods and insects when they were exposed to two different types of light sources. These studies showed altered insect flight activity in various arthropods [88], an altered flight activity in flying insects that leads to attraction toward urban and peri-urban night-time illuminated environments [82], and the attraction of flying terrestrial insects toward light sources with varied CCTs [83]. Two of the five studies defined a level of attraction in arthropods, insects, and spiders when comparing the amount of attracted organisms detected at the light sources [84,86]. Two studies reported that the degree of horizontally polarized light can potentially interact with illuminated man-made structures, which can induce attraction to ALAN in arthropods, insects, and spiders [94,95].

A total of four studies demonstrated a negative phototactic behavioral response (the opposite to positive phototactic, which refers to the avoidance by organisms of or their repulsive response toward a stimulus of light) in arthropods, insects, or spiders. The studies reported avoidance behavior in female arthropods (*Operophtera brumata*) [96], a lower propensity to fly toward light in urban moths when compared to moths from darker habitats [97], avoidance of ALAN as an anti-predator behavior in the tree weta (*Hemideina thoracica*) and cave weta (*Rhaphidophoridae*) [98], and a reduced light avoidance behavior in urban spiderlings that exhibited a choice of location for web building near illuminated areas [99].

Exposure to ALAN resulted in altered predator–prey interactions [100–104] in aphids and bean plants [100]; altered locomotor activity in male parasitoid wasp (Aphidius ervi) and its main host, the pea aphid (*Acyrthosiphon pisum*) [104]; and altered web selection for foraging and for prey capture in Australian garden orb-web spiders (*Eriophora biapicata*) [101]. Exposure to ALAN was shown to affect the abundance, community structure, density, and coverage of arthropods, insects, and spiders in a determined location. ALAN was observed to increase the abundance and diversity of insects compared to terrestrial predators as it alters the nutritional flux of aquatic webs to terrestrial food webs when habitats are artificially lit at night [105]. Furthermore, the biomass of attracted insects was affected by the moon illumination fraction (sometimes given as a percentage) [103]. Four studies reported an altered mating and courting behavior in arthropods when they were exposed to ALAN [96,106–108].

A higher number of mated female arthropods (*Operophtera brumata*) were observed in non-illuminated trunks, as a negative phototactic response to ALAN, which was observed to disrupt the reproductive behavior in female arthropods [96]. Female fireflies were observed not to flash when they were exposed to ALAN. No flashing light is an atypical behavior in fireflies compared to fireflies that were observed in darker locations, where female fireflies tethered at least once [106].

One study reported an altered courtship and an increase in mating behavior in Australian black field crickets (*Teleogryllus commodus*) when they were under ALAN [107]. However, another study under ALAN exposure observed a longer time initiating movement on exposure to ALAN, which appeared to potentially alter aspects of mate finding and exploratory behavior [108].

Four studies demonstrated an altered physiology and development in arthropods when exposed to ALAN [109–111]. When black-bellied fruit flies (*Drosophila melanogaster*) were exposed to a gradual increase in illuminance, oviposition (the process of laying eggs) was less likely to occur and even decreased. This was considered to affect the fecundity and survival rate of fruit flies [109]. Orb-web spiders (*Eriophora biapicata*) exposed to ALAN were observed to mature significantly earlier, and their growth was stunted. There was also an increased mortality rate and a reduced number of eggs produced by females, which was considered to decrease reproductive success and survival [110]. For *Apamea sordens*, exposure to ALAN was linked to a decrease in body mass gain and altered development during the larval stage [71]. Meanwhile, a prolonged egg period, a decreased hatch rate, a shortened larval development period, an increase in the larval survival rate, a decrease in fecundity per female, a decreased oviposition quantity per day, and a prolonged pre-oviposition and oviposition period were reported in *Mythimna separata* when they were exposed to ALAN [111].

5.1.3. Fish

A total of 28 studies demonstrated behavioral and physiological responses in fish when they were exposed to ALAN. The attraction to [120] or avoidance [121–125] of illuminated waters was observed to cause a behavioral response to ALAN. For instance, the attraction of fish toward illuminated water areas has been shown to be a response exhibited by various fish species, such as lance (*Ammodyteshexapterus* sp.), three-spined stickleback (*Gasterosteus aculeatus*), Pacific herring (*Clupea pallasi*), great sculpin (*Myoxocephalus polyacanthoscephalus*), and soft sculpin (*Psychrolutes sigalutes*) [120]. In contrast, lit water sections were avoided by European eel (*Anguilla anguilla*) [121,122], American eel (*A. rostrata*) [123], vendace (*Coregonus albula*) [124], and *B. boops* [125]. In this context, altered dispersal, movement, or migration patterns in fish have also been observed. For example, Atlantic salmon (*Salmo salar*) smolts showed a change in migration behavior when leaving their natal waters [126].

A delayed fry dispersal was shown in Atlantic salmon (*S. salar*) when they were exposed to ALAN [127]. Similarly, delayed dispersal timing and a disturbed diurnal pattern were found for Atlantic salmon (*S. salar*) under ALAN [128]. One study even suggested using artificial light to guide eels into safe waters [123].

Other changes in behavioral responses in fish that were exposed to ALAN were altered foraging behavior, habitat use, and invertebrate prey assembled at a determined location [129]. An altered predator–prey interaction was observed in zooplanktivorous juvenile rudd (*Scardinius erythropthalmis*) and their prey (*Daphnia pulex* × *pulicaria*) [130].

Changed physiological responses in fish that were exposed to ALAN include a suppression of melatonin production in Eurasian perch (*Perca fluviatilis*) [117–119], roach (*Rutilus rutilus*) [134] golden rabbitfish (*Siganus guttatus*) [135], and zebrafish (*Danio rerio*) [136]. In addition, when Atlantic salmon (*S. salar*) were exposed to ALAN, low cortisol rates were observed, which indicates altered stress perception [137], and juvenile, bonefish (*Albula vulpes*) exhibited elevated blood glucose and blood glucose concentrations [138]. When roach (*R. rutilus*) and Eurasian perch (*P. fluviatilis*) were exposed to ALAN, their blood concentrations of sex steroids (17β-estradiol; 11-ketotestosterone) as well as their mRNA expression of gonadotropins (luteinizing hormone and follicle stimulating hormone) were reduced. Larvae surgeonfish (*Acanthurus triostegus*) were observed to have a reduced thyroid hormone levels [139].

A total of two studies reported altered growth rhythms. For instance, larval fish Nile tilapia (*Oreochromis niloticus*) demonstrated low larval growth and feed conversion efficiency [140] and Atlantic salmon (*S. salar*) showed an increase in their growth and body weight, which may reduce the incidence of sexual maturation [141]. One study reported that ALAN had no significant effect on the growth rate of Atlantic salmon (*S. salar*). However, accelerated oocyte reabsorption was demonstrated, which might alter their basic pattern of growth.

5.1.4. Amphibians

A total of 12 articles described ALAN as an invasive component of night-time environments near aquatic and terrestrial habitats and a stressor of behavioral and physiological responses in amphibians. Amphibians are a highly vulnerable taxon group. The impact of ALAN is not always population threatening, but it can reduce resilience and, thus, increase vulnerability against other anthropogenic stressors. Disturbances of these species have to be avoided, and technological solutions that have less negative impact should be a priority.

ALAN was reported to alter amphibian behavioral responses, including the preference for shelter [148]; attraction toward urban edges, which might lead to an altered passage choice of habitats typically visited [149,150]; altered vocalization calls [151,152]; altered detection and consumption of prey [153]; altered attempts to capture prey [154]; increased activity [155]; and mate selection and reproductive success [156].

Physiological responses in amphibians when they were exposed to ALAN included reduced growth [157] and high production levels of neutrophil proportions and altered ratios of neutrophils to lymphocytes [158].

5.1.5. Reptiles

A total of eight articles reported ALAN as an invasive artificial condition that may have a detrimental impact on the natural habitat of reptiles and as a consequence, it may drive reptiles away from dark areas and distract them from their common behaviors at night. Two studies looked into the emergence of reptiles at night in illuminated locations. The attracted reptiles derived visual range sensitivities that were significantly stimulated by the wavelength composition of light sources with a broad SPD [160,161]. Artificially illuminated habitats appeared to trigger opportunistic foraging behavior in Moorish wall geckos (*Tarentola mauritanica*) for easily finding prey, which increased their foraging activity [162]. In addition, in the reptile organism group, four studies documented that different turtle species are adversely affected by the presence of ALAN when their aquatic habitats on coastlines and shores, specifically turtle nesting sites, are artificially illuminated by night [163–166].

Marine sea turtles, including loggerhead sea turtles (*Caretta mauritania* L.), green sea turtles (*Chelonia mydas*), hawksbill sea turtles (*Eretmochelys imbricate*), olive ridley sea turtles (*Lepidochelys olivacea*), flatback sea turtles (*Natator depressus*), and leatherback sea turtles (*Dermochelys coriacea*), were attracted to illuminated locations away from their nesting sites [163], which also deviated marine turtles from their nocturnal trajectories [164]. In addition, as their nocturnal behavior was affected by the presence of ALAN, it could incite the aggregation of marine turtles inland, away from the water [165]. In addition to an altered movement and trajectory pattern inland, ALAN may disturb the hatching behavior of marine turtles that arrive inland [166].

Eight studies demonstrated that exposure to ALAN in terrestrial and aquatic reptiles results in different behavioral responses that draws them, for example, away from their typical nocturnal habits and to illuminated areas [160–167].

5.1.6. Birds

A total of 76 articles revealed evidence of individual impacts of ALAN on birds. Among these studies, ALAN was considered an invasive stressor that reaches bird nests at night, particularly nests in proximity to urbanization [168]. ALAN was shown to alter behavioral responses during flight, migration, rest, and active periods during both night and day, as well during breeding periods and the egg-laying process [169–171]. Furthermore, ALAN was reported to impact physiological responses that involved altered reproduction [172], development [173,174], body mass [175], and hormonal levels [176–179].

Studies related to the attraction and disorientation of birds during flights or migration at night described ALAN as a subjective visual barrier that can potentially affect the ability of birds to locate stopover sites during flights [180]. ALAN also impedes the perception of migrating routes during seasonal avian migration [181,182], which can lead to looped migrations [183], grounded flying birds [184], collisions against tall buildings [185], and the injury or death of nocturnally migrating birds [186].

A total of 6 studies reported altered behavior during flights at night or during migration [180,181,187–190]. Flying Leach's storm-petrels (*Oceanodroma leucorhoa*), European storm-petrels (*Hydrobates pelagicus*), and Manx shearwaters (*Puffinus puffinus*) were reportedly grounded when they were exposed to ALAN during nights with moon visibility (with less than 20% of the moon's face illuminated) [187]. Nights with a visible new moon at approximately 0.1–0.3% coincided with grounded Hutton's shearwater fledglings (*Puffinus huttoni*) [191]. A consistent pattern of grounded Newell's shearwaters (*Puffins newelli*) was shown near coastlines [192]. During migration, when basra reed warbler (*Acrocephalus griseldis*) and the sakhalin leaf warbler (*Phylloscopus borealoides*) are exposed to ALAN [189,190], their orientation and navigation cues can be altered, which can potentially lead to destination shifts and changes in flying routes [181].

Fifteen studies showed altered activity or efficacy in birds when they were exposed to ALAN [179,193–206]. A total of three studies demonstrated altered foraging behavior in birds when they were exposed to ALAN [207–209]. For instance, longer foraging periods were observed in urban blackbirds (*T. merula*) [210]. Mockingbirds (*Mimus polyglottos*) were reported to feed their nestlings later in the night [207]. Redshanks (*Tringa totanus*) spent less time foraging during the new moon and on clear nights [208]. Nighthawks were observed foraging at higher locations in illuminated areas [209].

A total of nine studies reported altered timing for singing in birds when they were exposed to ALAN [211–219]. An altered timing for singing was reported in European robins (*Erithacus rubecula*), blackbirds (*T. merula*), great tits (*P. major*), and blue tits (*C. caenleun*) [211]. Chaffinches (*Fringilla coelebs*), blue tits (*C. caenleun*), great tits (*P. major*), blackbirds (*T. merula*), and robins (*E. rubecula*) showed altered communication and singing patterns, which affected reproductive behavior when they were exposed to ALAN [212]. Four studies showed an onset of dawn singing in birds [213–216]. One study demonstrated no impact of ALAN on the dawn singing behavior of birds [217]. One study reported that ALAN and noise pollution did not affect dawn singing. However, social factors were acknowledged to induce earlier singing behavior in male house wrens (*T. aedon*) [218]. For wood pigeons (*Columba palumbus*), ALAN did not affect their calling activity [219].

A total of nine studies reported altered sleep in birds when they were exposed to ALAN [195–197,220–225]. One study reported no altered night-time sleep behavior in great tits (*P. major*) when they were exposed to ALAN [226].

Studies that investigated physiological responses to the exposure of ALAN observed advanced reproductive maturity in urban blackbirds (*T. merula*) [172], a preference for illuminated nest selection in urban blackbirds (*T. merula*) [227], an early onset of gonadal development, an early onset of hormonal secretion in urban blackbirds (*T. merula*) [173], lower levels of testosterone in female blackbirds (*T. merula*), no increase in body mass for nestling great tits (*P. major*) compared to great tits in dark locations, altered sexual selection process [175], altered gonadal growth in male great tits (*P. major*) [174], elevated corticosterone hormone in great tits (*P. major*), accelerated reproductive endocrine activation of the hypothalamic–pituitary–gonadal axis in tree sparrows (*Passer montanus*), low levels of estradiol in female and male scrub-jays (*Aphelocoma coerulescens*) [176], an earlier increase of luteinizing hormone, a lower peak in the secretion of luteinizing hormone, lowered levels of testosterone and estradiol in urban tree sparrows exposed to ALAN, and lowered or suppressed melatonin levels [177–179].

Lastly, five studies reported ALAN and noise pollution as environmental factors that can affect the density [222] and activity of birds [228,229] at night in an illuminated location.

5.1.7. Non-Human Mammals: Bats, Primates, Rodents, and Marsupials

Non-human mammals are considered a threatened organism group due to the expansion of ALAN [160,245]. A total of 11 studies reported an altered behavior in bats when they were exposed to ALAN. *Pipistrellus nathusii* and *Pipistrellus pygmaeus* exhibited attraction toward illuminated locations [246]. One study showed that *Pipistellus* spp. were one of the most abundant and active species at night [247]. Noctules (*Nyctalus noctula*) displayed attraction toward ALAN, which led them to forage near ALAN [213]. One study reported bat activity at night and calls made by lesser noctules (*Nyctalus leisleri*) as a behavioral response to the density of luminaires and the type of light source [248]. In contrast to this behavior, two studies presented a repulsive behavior toward ALAN in lesser horseshoes (*Rhinolophus hipposideros*), *Myotis* spp., and Sowell's short-tailed bats (*Carollia sowelli*) [249,250]. One study reported an increase in activity at night when bats were exposed to ALAN [194]. For instance, Pond bats (*Myotis dasycneme*) demonstrated an altered flight path [251] and Lesser horseshoe bats (*Rhinolophus hipposideros*) [23,252], Kuhl's pipistrelles (*Pipistrellus kuhlii*), and Botta's serotine bats (*Eptesicus bottae*) [251] showed altered flying behavior and trajectories.

A total of three studies demonstrated altered behavioral and physiological responses in primates when they were exposed to ALAN. For instance, female Japanese monkeys (*Macaca fuscata fuscata*) had suppressed melatonin [254]. Gray mouse lemurs (*Microcebus murinus*) showed delayed nocturnal emergence [255], a high core temperature, and short locomotor activity [256] when they were exposed to ALAN.

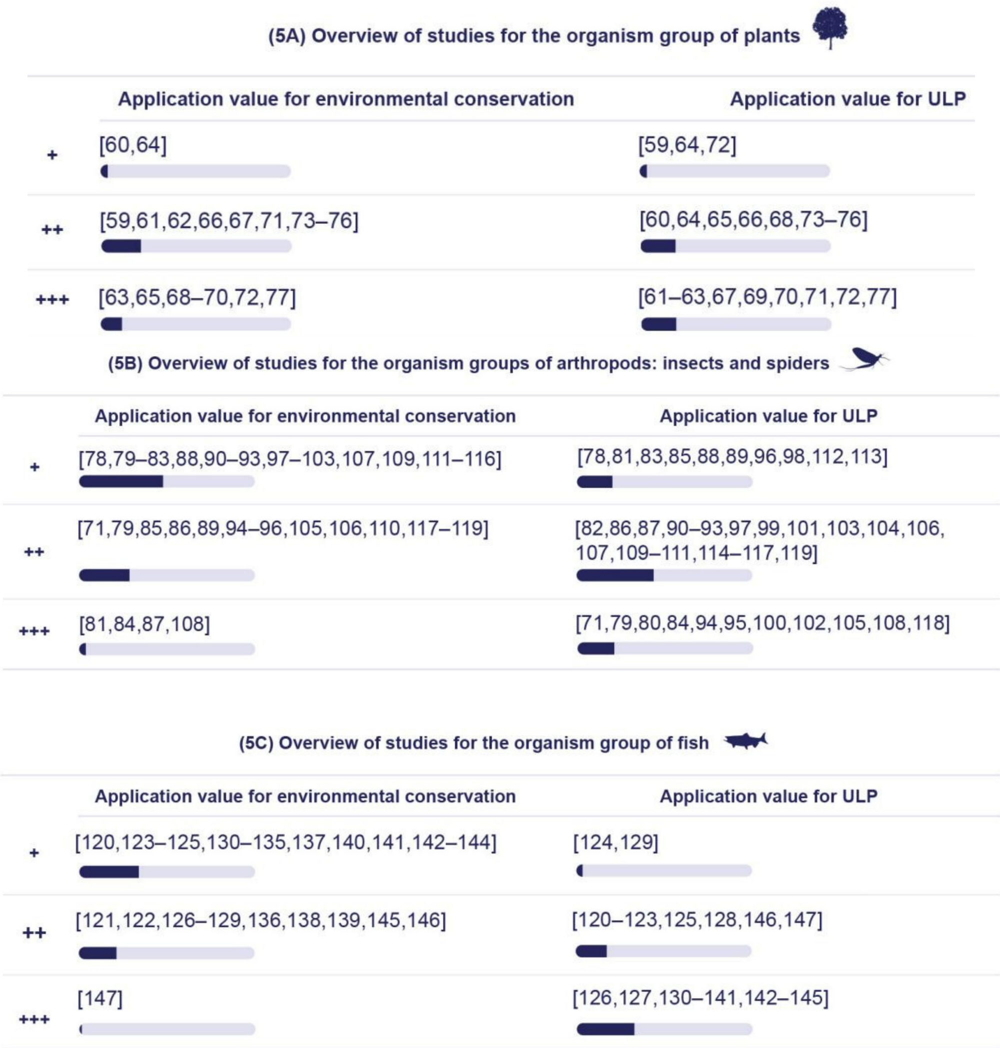
A total of nine studies investigated behavioral and physiological responses in rodents when they were exposed to ALAN. Three studies on rodents demonstrated suppressed or decreased activity when they were exposed to ALAN [257–259]. In contrast, two studies reported increased activity in rodents when they were exposed to ALAN [260,261]. Rodent bank voles (*Myodes glareolus*) showed increased activity and altered use of space during the quarter moon and the new moon. In this same study, males showed greater body mass compared to females [260]. One study reported delayed sleep, increased glucocorticoid (an indicator of induced stress), and behavioral arousal in Male *C57BL/6* when they were exposed to ALAN [261]. Three studies reported physiological responses in rodents when they were exposed to ALAN, involving an increase in testes size [174], an altered core temperature [262], a remodeled retina, a noticeable reduction of the outer nuclear layer of the retina [263], and an impaired and healing process [264].

A total of four studies reported behavioral and physiological responses in marsupials when they were exposed to ALAN. One study showed increased foraging activity and a decrease in time spent avoiding predators in Tammar wallabies (*Macropus eugenii*) [265]. Two studies reported reduced or suppressed melatonin in Tammar wallabies (*Macropus eugenii*) when they were exposed to ALAN [167,266]. One study reported no effect on the activity and behavior of wombats (*Vombatus ursinus*) when they were exposed to ALAN [161].

5.2. Translating ALAN Research into Applicable Lighting Practice

5.2.1. Application Value for Environmental Conservation

Figure 5A–G presents the application value that each study offers for environmental conservation and the required level of ecological knowledge. Two researchers identified and assessed the appropriateness of the application value each study offered and assigned a ranking system that allows the identification of the application value offered by each study following its reference number. The application value for environmental conservation is assigned as follows: "+" if the study presents relevant findings on the effects of ALAN on organisms, "++" if the study presents a significant impact of ALAN with an indication of adverse stress on organisms, and "+++" if the study presents adverse effects of ALAN with ecological relevance. The application value for ULP assigns three different ranks to classify studies based on the required level of ecological knowledge: "+" if the content of the study is considered easy to understand by a lighting professional to raise awareness on the impact of ALAN on an organism group, "++" if the content is considered academic and a basic knowledge of ecological concepts is required, and "+++" if the content of the study requires proficient knowledge in ecology for a better understanding of the study's results.



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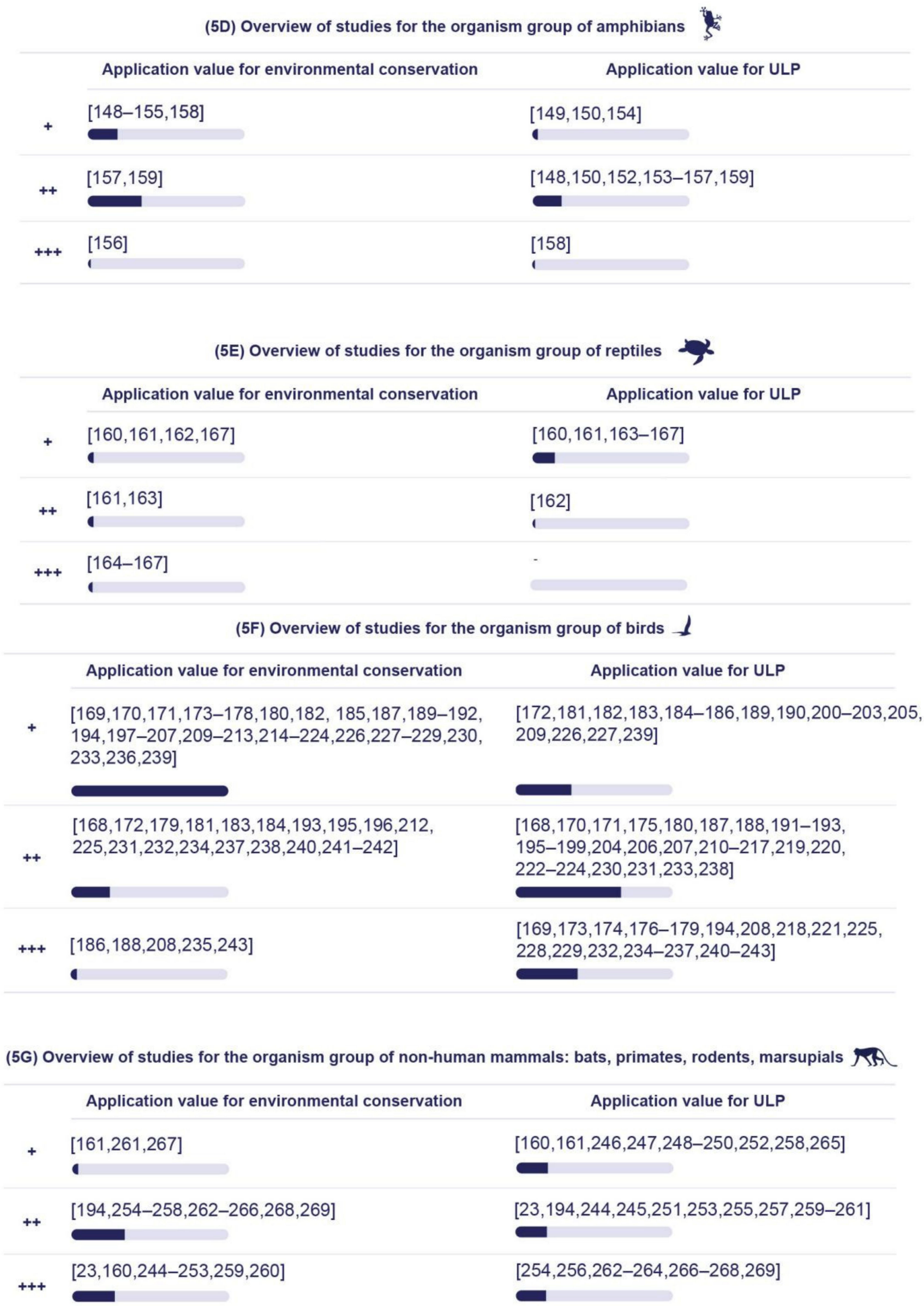


Figure 5. Overview of all studies with assigned application values for environmental conservation and ULP. See the text for details.

5.2.2. Physical Properties of Artificial Lighting Based on the Responses of Various Organism Groups

Figure 6 shows the physical properties of artificial lighting that are identified or if no results were identified in varied organism groups. Varied usage of physical quantities was identified when describing ALAN. Illuminance was reported across all taxa, and irradiance for fish, birds, and plants (in the PAR band as PPFD) was used as a parameter to describe light intensity. Luminance and radiance were rather uncommon. SPD and CCT were reported for almost all taxa and lamp type for all taxa. A significant number of studies reported the continuous exposure of ALAN to address ALAN operating from dusk to dawn. Only two studies reported a periodic exposure to ALAN, with a determined interval of time. For the organism group of birds, flicker was commonly reported in various articles as a component to consider in light that can potentially alter avian responses.

Category of organism groups

Category of physical parameters of light	Plants	Arthropods, Insects, and Spiders	Fish	Amphibians	Reptiles	Birds	Mammals (non humans)
Iluminance	+	+	+	+	+	+	+
Irradiance	-	-	+	-	-	+	-
PPFD	+	-	-	-	-	-	-
Luminance	-	-	-	-	-	-	-
Radiance	-	-	-	-	-	-	-
Luminous Flux	+	+	+	-	-	-	-
PFD	+	-	-	-	-	-	-
SPD	+	+	+	+	-	+	+
CCT	+	+	+	+	-	+	+
CRI	-	-	+	-	-	-	-
Flicker	-	-	+	-	-	+	-
Linear Polarisation	-	+	-	-	-	-	-
Light Source	+	+	+	+	+	+	+
Duration	+	+	+	+	+	+	+
λp	+	+	-	-	-	-	+

Plants | Arthropods, Insects, and Spiders | Fish | Amphibians | Reptiles | Birds | Mammals (non humans)

Figure 6. Physical properties of light as reported per organism groups. "+" indicates it was reported. "-" indicates it was not reported.

5.2.3. The Identified Light Sources

A significant number of studies identified terrestrial organisms, such as birds, that were exposed to direct ALAN and LEDs. There are five categories of organism groups that were reported as being exposed to direct ALAN and LEDs. Fewer studies presented a comparison of an organism group when it was exposed to natural light conditions at night, for example, moonlight, and an artificial light source. The majority of studies focused on reporting behavioral or physiological responses when an organism group was exposed to one type of light source. Table 4 shows the identified types of light sources for each category of organism group.

Table 4. Overview of the number of studies based on the identified light sources and the organism group each study investigated. The category of light sources presents two variations of ALAN, which are defined as follows: "ALAN (dir.)" refers to a point light source and "ALAN (indir.)" refers to indirect skyglow. "-" indicates that no studies were identified for that category.

Category of Artificial Light and Light Sources	Category of Organism Groups						
	Plants	Arthropods: Insects and Spiders	Fish	Amphibians	Reptiles	Birds	Non-Human Mammals: Bats, Primates, Rodents, and Marsupials
ALAN (dir.)	10	6	4	2	4	16	8
ALAN (ind.)	-	3	5	4	2	28	4
CMH	-	-	5	-	-	2	-
FL	1	5	2	1	-	4	2
HPS	-	5	2	1	-	1	3
LED	7	15	6	4	1	23	8
LPS	-	-	-	-	-	-	-
CMH and LED	-	-	2	-	-	-	-
CMH, HPS, and LED	-	2	-	-	-	1	-
CMH, HPS, and TH	-	-	1	-	-	-	-
CMH, HPM, LED, and LPS	-	1	-	-	-	-	-
FL and LED	-	2	1	-	-	-	1
HPS and HPM	-	1	-	-	-	-	-
HPS and LED	1	1	-	-		-	-
HPS, LED, and induction lamp	-	-	-	-	-	-	1
HPS, MH, LPS, and LED	-	-	-	-	1	-	-
LED and HPM	-	2	-	-	-	-	-
ALAN and moonlight	-	-	-	-	-	1	2
LED and moonlight	-	-	-	-	-	-	1

A total of 18 studies, compared two different light sources (2 studies on the impact of CMHs and LEDs on fish; 2 studies on the impact of CMHs, HPSs, and LEDs on the arthropods insects and spiders; 1 study on the impact of CMHs, HPSs, and THs on fish; 1 study on the impact of CMHs, HPMs, LEDs, and LPSs on the arthropods insects and spiders; 2 studies on the impact of FLs and LEDs on the arthropods insects and spiders; 1 study on the impact of FLs and LEDs on fish; 1 study on the impact of FLs and LEDs on non-human mammals, such as bats, primates, rodents, and marsupials; 1 study on the impact of HPSs and HPMs son the arthropods insects and spiders; 1 study on the impact of HPSs and LEDs on plants; 1 study on the impact of HPSs and LEDs on the arthropods insects and spiders; 1 study on the impact of HPSs, LEDs, and induction lamps on non-human mammals, such as bats, primates, rodents, and marsupials; 1 study on the impact of HPSs, MHs, LPSs, and LEDs on reptiles; and 2 studies on the impact of LEDs and HPMs on the arthropods insects and spiders).

Figures 7–9 show an overview of the varied organism groups, the type of ALAN, and the three identified physical parameters (illuminance, SPD, and CCT). The types of ALAN are categorized as direct ALAN (dir.), which refers to a point source, and indirect ALAN (ind.), which refers to artificial skyglow. Illuminance was categorized as dim for illuminance below 10 lx, low for illuminance between 10 and 50 lx, mid for illuminance between 50–100 lx, and hi for illuminance between 100 and 200 lx. The SPD was categorized as UV for ultraviolet wavelengths (<400 nm), SW for short wavelengths below 500 nm, MW for midwavelengths of 500–550 nm, and LW for long wavelengths of 550–780 nm. CCT was categorized as warm for a CCT < 3300 K, neut for a CCT of 3300–5300 K, and cold for a CCT > 5300 K.

Figure 7 summarizes studies where ALAN is described unspecifically (i.e., no detailed information of lamp type, etc., is given).

Figure 8 summarizes studies with a specific lamp type given and single sources being investigated (e.g., CMHs or LEDs).

Figure 9 summarizes studies with specific lamp types given and where multiple light sources were compared (e.g., CMHs and LEDs).

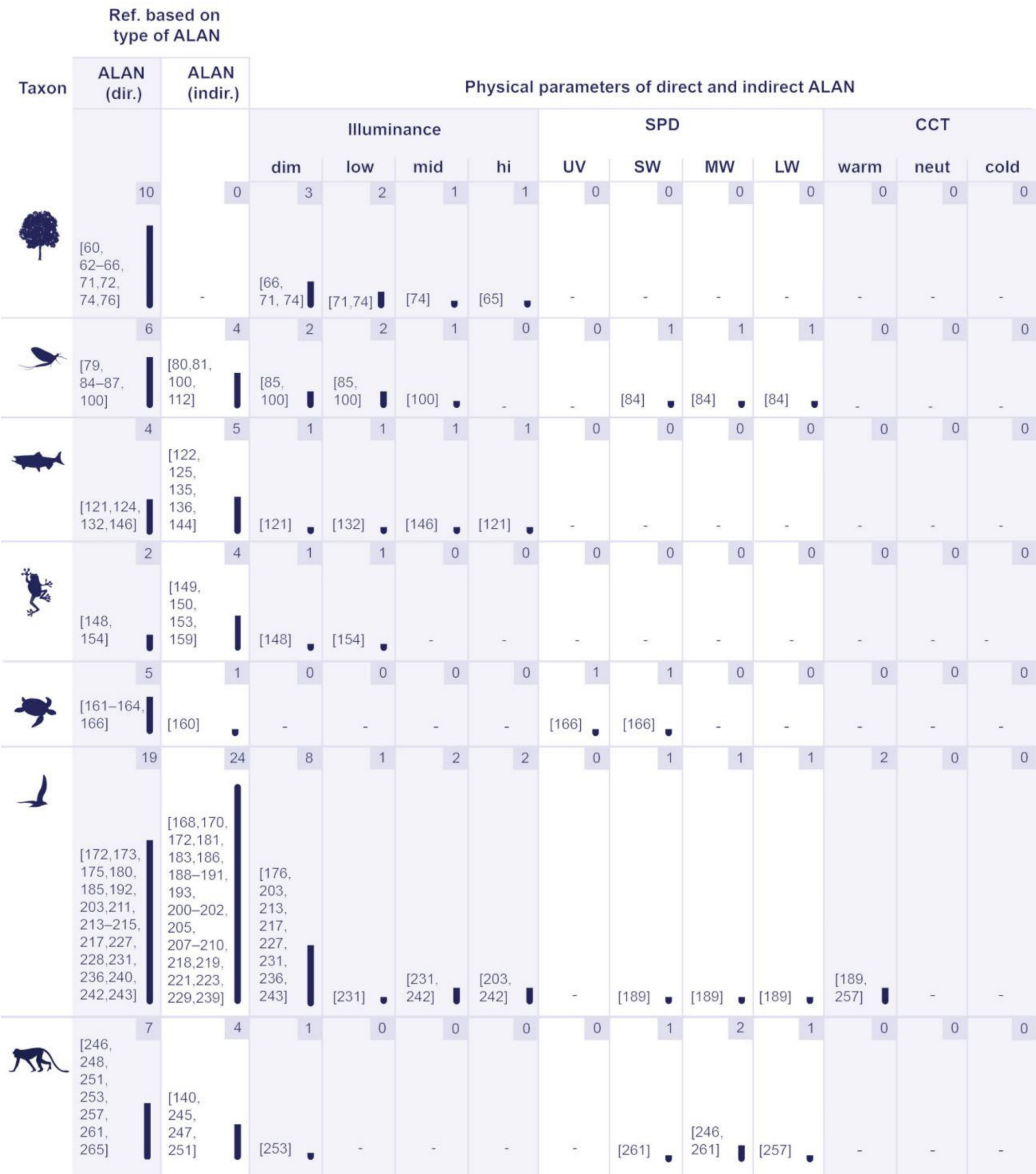
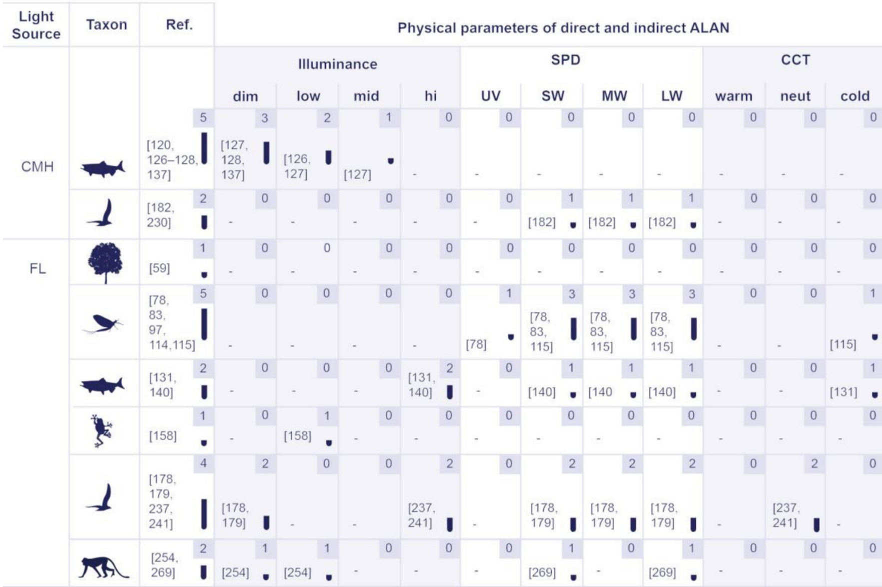
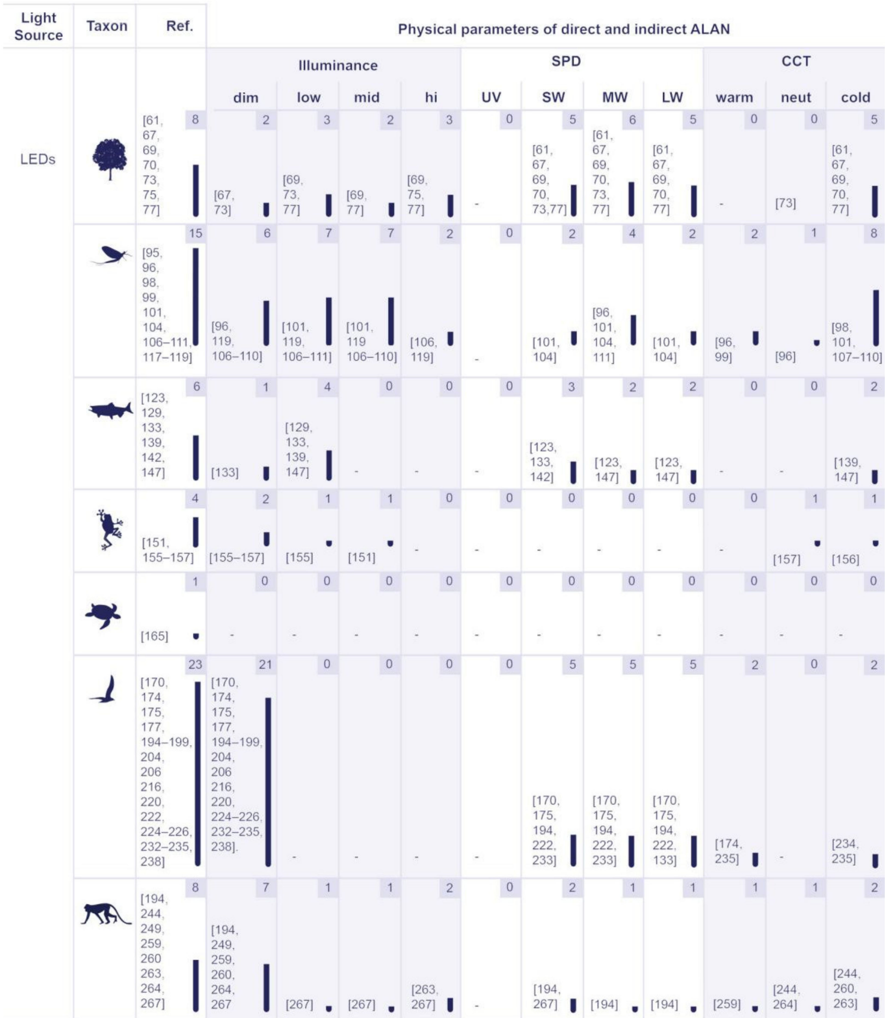


Figure 7. Reported physical parameters per organism group. See the main text for details on categories.

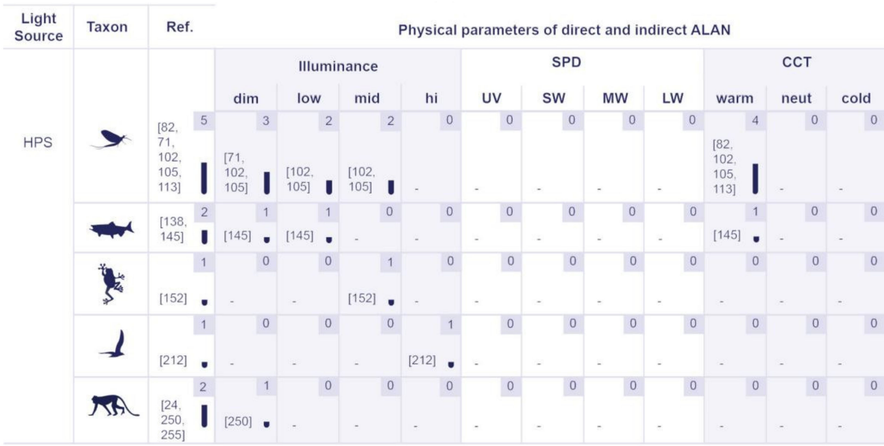


(**a**)



(**b**)

Figure 8. *Cont.*



(**c**)

Figure 8. (**a**) Reported physical parameters per organism group for different (single) CMHs and FLs. See the main text for details on categories. (**b**) Reported physical parameters per organism group for different (single) LED light sources. See the main text for details on categories. (**c**) Reported physical parameters per organism group for different (single) HPSs. See the main text for details on categories.

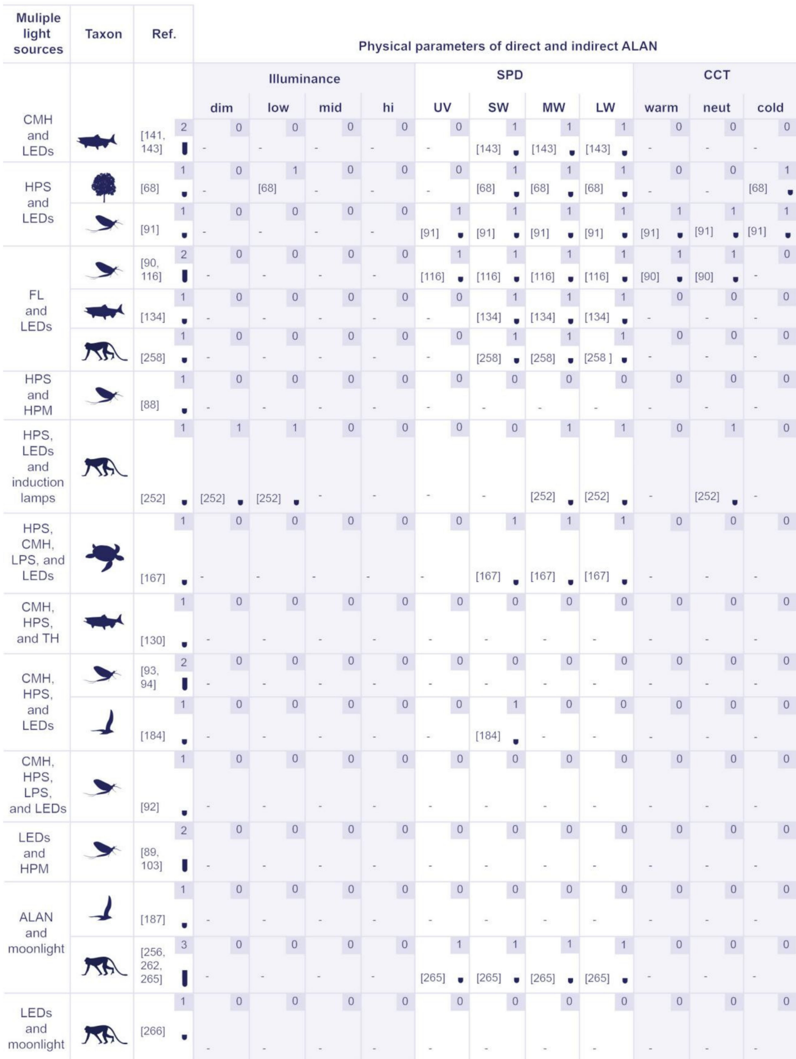


Figure 9. Reported physical parameters per organism group for different (multiple) light sources. See the main text for details on categories.

6. Limitations of the Study

Despite the contributions mentioned in Section 5, this systematic review study has its limitations, which are identified below:

6.1. Experimental Setting (Laboratory and Field Studies) versus Applied Outdoor Lighting

To examine the impact of ALAN on the behavioral and physiological responses in flora and fauna, the review was based on published data. However, results from experiments performed in a laboratory environment might be different from the results from similar experiments undertaken in a more complex, real-world environment and, in the end, may cause different interpretations.

6.2. Research Methodology

There is a lack of proper research methodology to conduct environmental research in relation to the impact of urban lighting on flora and fauna. This includes establishing specific, commonly approved lighting parameters to allow for the reproducibility of research, as they form the knowledge foundation on which future studies are built.

6.3. Language of the Reviewed Studies

Although significant research has been performed all over the world by non-native English researchers in various languages, in our review, we only focused on studies written in English because this is the dominating scientific language. We are aware that when language is a barrier for the work being reviewed, widely shared, and understood by others, that this selection process may have omitted some important data.

6.4. Sample Size (Number of Reviewed Research Studies and Publication Bias)

The number of studies considered for a systematic review depends on the keywords, the electronic database, and the defined inclusion criteria used [55–58]. Furthermore, there are almost no published examples in which no effect was documented, which suggests either that biological effects are fairly widespread or that there is a potential for strong publication bias. Whereas some problem with publication bias would not be surprising, the reality most likely lies somewhere in between [270].

7. Discussion

The varied negative effects of ALAN on organism groups are partly investigated and understood by ALAN researchers. However, lighting professionals often struggle to understand these complex findings and on how to apply them into solutions for day-to-day ULP. Therefore, in this paper, we present relevant parameters of artificial lighting that can be applied to minimize its negative effects on the natural environment and to aid in the assessment of ecological conservation.

Existing research on ALAN as an environmental stressor [17,18,20,271,272] indicates strong behavioral and physiological responses of individual organisms, with potential impacts on population communities and entire ecosystems. For instance, the book by Rich and Longcore is the first collection of scientific chapters on potential impacts on mammals, birds, reptiles and amphibians, fish, invertebrates, and plants when they are subject to ALAN. This unique research provides essential information on how ALAN can affect the behavior and physiology across taxonomic groups. However, little attention is being paid yet to the description of the artificial lighting conditions, which includes the light sources and the physical parameters of artificial light known to affect the mentioned taxonomic groups, in order to better understand the components in the applied light, which raises concern [271]. Gaston et al. [17] developed a framework to put forward space (the location at which ALAN is applied), time (the duration of operating ALAN), and wavelength composition (the spectral signature of ALAN) as three crucial components to consider in ALAN that can potentially affect biological systems (i.e., visual system in animals, photosynthetic system in plants, or non-visual pigments in plants and animals) and how light is distinguished as a resource (i.e., for the photosynthetic process in plants to occur, for the distinction of night and day) or as an information source (i.e., photoperiodism, visual perception, and spatial orientation). Their framework addresses ALAN principles applicable for a better understanding of the impact of ALAN on species and ecosystems [17]. Schroer and Hölker reviewed the perception of light and photoreceptors, and they detail that the time and duration for which luminaires operate, the color spectra of the emitting sources, and the intensity, as well as the position of luminaires and the direction of light at night, can impact various organism groups, including plants, arthropods, fish, amphibians, birds, reptiles, and mammals. The review concludes with recommendations for three parameters of artificial light. This includes the lowest illuminance level required for its use; the avoidance of spectral distribution rich in short wavelengths as it can alter circadian signals for higher vertebrates, including humans; and the restriction of the direction of light to areas where it is needed. The authors emphasized the importance of avoiding illuminating areas where endangered species live (e.g., natural habitats of aquatic species) and, in general, natural blue and green spaces in urban areas (as long as security and safety requirements are not compromised), as well as natural darkness reserves and corridors for the movement of nocturnal species, such as fish and bats. Despite this, light sources considered for urban lighting applications were not addressed in the review to better comprehend the components applied across nightscapes and their impact on varied organism groups [18]. Furthermore, Grubisic et al., via a systematic review of impacts of ALAN on melatonin production in vertebrates (fish, amphibians, reptiles, birds, and mammals, including humans), concluded that melatonin is suppressed, for some fish species even at an illuminance as low as 0.01–0.03 lx. They also found that melatonin is suppressed at 6 lx for sensitive humans and at much lower illuminances for monochromatic light in the melanopic band. The study provides insights into the disruption of natural photic environments, circadian rhythms, and photoreceptor systems. However, including the type of light source and other physical parameters (i.e., spectral distribution) of the exposed light could aid in understanding the artificial light factors that prevent the production and synthesis of melatonin [20]. Sanders et al. reported via a meta-analysis that when taxa were exposed to ALAN, responses were dominated by changes in physiology, the life history trait of organism groups, the population, and community-based measures. The study briefly mentions that the timing, intensity, and spectrum of artificial light should be restricted to when it is genuinely required by users, humans, to therefore, minimize its ecological impact. Yet, the light sources and physical parameters of the artificial light that induces changes in responses were not addressed to better comprehend the light-polluted scenarios that varied organism groups are exposed to [272]. Recently, Hölker et al. addressed fundamental knowledge gaps, ranging from basic challenges on how to standardize light measurements, through the multi-level impacts on biodiversity, to opportunities and challenges for more sustainable use [273]. All these reviews gather crucial evidence on the night-time environment as a temporal niche in an ALAN context. They address in depth the adverse impact of artificial light at night at the wrong time and place, with unnatural brightness and colors, on biodiversity. In addition, the reviews provide statements about appropriate solutions to the problem as a crucial and straightforward task. The evidence gathered by ALAN researchers indicates that a paradigm shift must happen in the lighting approaches currently used in ULP. However, the lack of detailed information about the applied artificial light across studies, particularly the light sources and the physical parameters that were used, does not adequately inform ULP as there is insufficient information about the parameters to avoid and the ones that can be applied. This lack of information manifests a disconnection between ALAN research, the ULP (i.e., architectural and urban lighting designers and electrical illuminating engineers), and the experts involved in the lighting sector.

Our review shows that varied organism groups experience a wide range of alterations under ALAN (as a single source, as multiple sources, and as an indirect component in a nocturnal landscape). It also shows that wavelength-dependent responses of affected behaviors and physiological processes vary among species. The widespread use of ALAN with continuous emitted light from dusk to dawn, with illuminance levels that mask natural low-light conditions, such as moonlight and starlight; emissions directed toward the sky or downward, toward water bodies, or other natural environments; and emissions rich in short wavelengths and with high CCTs (or a better measured SPD) should be important factors that are taken into account in ULP. The majority of the literature gathered by ALAN researchers confirms that the operating time, illuminance, direction, and spectral appearance of light sources can alter night and day cycles and the actual physical nightscape, which needs protection.

Most studies explored the behavioral and physiological responses of an organism group when it was exposed to direct ALAN (50 studies), while fewer studies explored the potential impact of indirect ALAN across all organism groups (46 studies). However, these studies lacked detailed descriptions that might clarify the stressor parameters observed to alter changes in organism groups.

A large number of studies across all organism groups were focused on LEDs (64 studies). The second-most-studied impact of a light source across all organism groups, except for plants and reptiles, involved HPSs (21 studies). The third-most-studied impacts of a light source across all organism groups (except for reptiles) involved FLs (15 studies). This suggests that the research field recognizes the global shift from conventional lighting toward solid-state lighting in recent years [13]. However, several studies were excluded from this systematic review, as they focused on light sources that are hardly used anymore in urban lighting practice (e.g., incandescent lamps, tungsten halogen lamps, and high-pressure mercury vapor). Instead, our review gathers studies that report the impact of light sources typically considered for urban lighting, including HPSs, LPSs, LEDs, and FLs.

Most of these studies concerning single light sources showed the impact of three different light parameters: (1) broad spectral distributions, including short, mid, and long wavelengths; (2) illuminance levels below 10 lx, and (3) CCTs of 3300–5300 K. Meanwhile, when multiple light sources were compared, only their spectral power distribution was considered. This supports the need for a consensus on measuring and reporting physical parameters of artificial light sources, as it is necessary to properly address the components of artificial light known to be stressors [273].

Fewer studies addressed and compared artificial light with natural light conditions, such as moonlight (two studies on ALAN and moonlight and one study on LEDs and moonlight). This suggests that our knowledge about the extent that artificial light at night can potentially mask natural light conditions still needs to be explored.

Recommendations for Future ALAN Research and Urban Lighting

Future ALAN research should define the type of light source that is used, as well as the physical parameters of the artificial light that is emitted, for a better comprehension of the lighting conditions considered to cause a disruption and to better communicate and translate the potential implications across taxa. Moreover, it is recommended to use ALAN as a term to address studies related to artificial lighting conditions.

It is obvious that ALAN researchers tend to provide different quantities and use different units than lighting professionals. It is crucial for mutual understanding that both groups, ALAN researchers and ULP, try to provide both photometric and radiometric quantities and units (i.e., illuminance in lx and irradiance in W/m^2) and ideally an SPD (in W/m^2 nm).

Often, studies focus on the continuous exposure of ALAN (from dusk to dawn). Future studies should also consider addressing the periodic exposure to ALAN (for a determined time at night) across taxa.

Furthermore, the exposure to weather and varied atmospheric conditions is rarely considered in research studies that provide evidence on a changed behavior or physiological change. Future ALAN research should include weather and varied atmospheric conditions (i.e., cloudy days and clear sky) and varied natural light conditions (i.e., lunar phases) when measuring the varied parameters of illuminated nightscapes, which can provide a better understanding of the exposed environment [54,273].

Visual ecology has become a subject of increasing interest among ALAN researchers. Future studies should also explore commonly used light sources for outdoor night-time illumination at varied illuminances in relation to how artificial light at night might impact visual ecology among organism groups [274].

In the past, only a handful of studies addressed two recently explored physical parameters of ALAN, flicker and polarization [94,95,275], and our review does not cover these two parameters in detail as only three studies focused on arthropods reporting polarization as an important parameter for mayflies. Flicker was reported as an important parameter of light in two studies for migrating birds. However, as our current knowledge on the impact of these two parameters remains limited, future ALAN research should acknowledge the degree of polarization and flicker as parameters that can induce a negative response in flora and fauna.

This systematic review tailors ecological knowledge for lighting professionals so they can better understand that artificial lighting can potentially affect individual organisms differently and that the physical parameters of artificial lighting must be carefully managed to minimize the negative impact of ALAN when applying light at night in cities and towns so no organism, ecosystem, or habitat is injured when outdoor lighting is applied. Translating research findings about ALAN implies that ULP must consider the night as a natural resource that needs protecting, with its inhabiting organisms, rather than only addressing tailored solutions for endangered species [34,273,276].

8. Conclusions

While the use of artificial illumination has exponentially increased in recent years, and applied lighting technologies have become present across urban and natural environments, ALAN as an anthropogenic pollutant can still be reduced and better controlled by wisely addressing three challenges. These challenges involve (1) rethinking the human-centric approach in ULP, (2) improving communication between ULP and ALAN research, and lastly (3) developing transferable knowledge between these two domains and establishing relevant environmental parameters for urban lighting.

Firstly, these days, urban lighting focuses on mainly presenting the visual experience of nightscapes [33] as well as providing lighting for the safe passage of pedestrians or vehicles, often neglecting natural environments and biodiversity [15,273] and unintentionally polluting naturally dark skies [277]. Therefore, we postulate that lighting professionals involved in ULP should rethink their user-centered approach and become aware of ALAN research. They should also embrace a broad understanding of the detrimental effects of ALAN on natural environments by acquiring ecological knowledge to realize sustainable lighting design that maximizes environmental conservation while also providing safety and security.

Secondly, a shift in the current forms of communication is necessary to bridge between ALAN research and ULP in order to adopt solutions and to instigate an open and collaborative communication between the domains. This approach can help to interpret the challenges, identify boundary concepts, and translate the results developed by each domain [22,273]. The introduced conceptual communication framework (CCF) might serve as a strategy to encourage a collaborative mode of knowledge construction (Figure 10). CCF combines the interests and values of each domain and the knowledge infrastructure offered. It assigns (a) a lighting foundation, as a starting point to define the essential knowledge required by both domains to comprehend the robust nature involved in the ULP and ALAN research, and (b) identifies an environmental ceiling as the boundary necessary for environmental conservation.

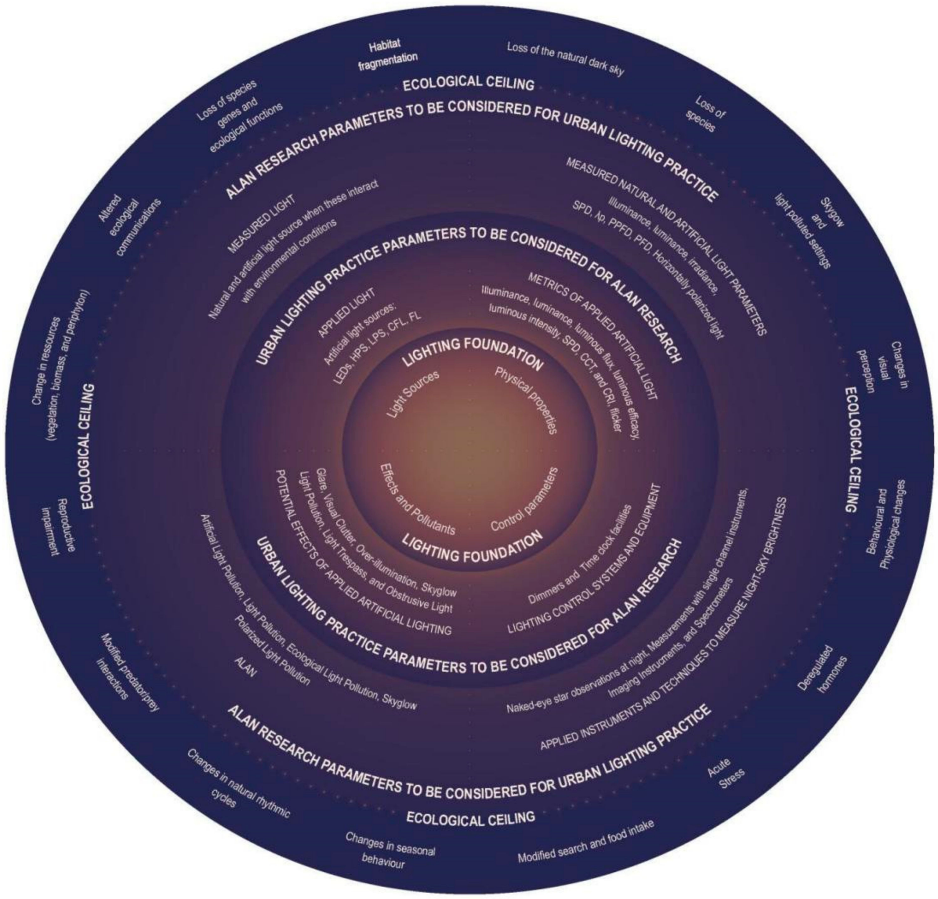


Figure 10. The communication framework and knowledge infrastructure diagram presents four cluster rings, which include the following key components: (a) lighting foundation, (b) ULP parameters to consider for ALAN research, (c) ALAN research parameters to consider for ULP, and (d) an ecological ceiling, inspired from Doughnut Economics [278]. Authors' elaboration.

Lastly, the difficulty of efficiently translating scientific results between domains hampers developing ecologically friendly and sustainable lighting solutions that consider flora and fauna [279].

For future studies, it is therefore recommended that ALAN researchers consider for their experiments, and for lighting professionals, to consider in their projects, both radiometric and photometric characterization of the artificial light sources used, based on the International System (SI) of units. Additionally, we recommend the development of a common measurement and reporting strategy for physical quantities and units to mitigate potential misunderstandings [20,54] (see, e.g., Kalinkat et al. [54] or Appendix of Grubisic et al. [20]). This collaborative work in the form of systematic review between ULP and ALAN research marks a new chapter in better communication between the two domains and supports more sustainable lighting approaches across nightscapes that involve the protection of the naturally dark skies, flora, and fauna.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14031107/s1. Tables S1–S6 shows an overview of the responses in 6 organism groups when exposed to a type of light source and the physical properties of ALAN.

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Appendix A. Terminologies and Definitions Connected to Natural and Artificial Light

While performing interdisciplinary research, many lighting professionals may be unfamiliar with the meaning of biologically related terms, which can result in misunderstanding. Therefore, to enhance comprehension, communication, and collaboration, a list of explanations and descriptions of specific terminologies and definitions has been created (Tables A1–A3).

Figure A1. (**a**–**l**) Various natural day-time and night-time conditions, including light generated by living organisms. Sources: (**a**) John Westrock/Unsplash, (**b**) Harry Knight/Unsplash, (**c**) George Hiles/Unsplash, (**d**) Nelson Santos Jr/Unsplash, (**e**) Paul Esch Laurent/Unsplash, (**f**) Clint Mackoy/Unsplash, (**g**) Lester Salmins/Unsplash, (**h**) Nathan Anderson L./Unsplash, (**i**) Claudio Schwarz Purzlbaum/Unsplash, (**j**) Leon Mengoli/Unsplash, (**k**) Andrew Wallace/Unsplash, and (**l**) Jessica Lucia/Flickr (CC BY-NC-ND 2.0).

Table A1. Overview of terminologies and definitions of natural and artificial light sources relevant for ALAN research and ULP [13,21,47,280–290].

Natural Energy Source	Terminology	Definitions
Sunlight	Sunrise/Sunset	The period when the Sun is at the horizon (at 0°); typical illuminance ca. 800 lx [280].
	Daylight	Solar radiation that reaches the Earth. This includes direct illumination and diffuse illumination from light scattered by air molecules, aerosol particles, cloud particles, or other particles in the atmosphere [281].
	Twilight	The illumination of the lower atmosphere when the Sun is below the horizon [281,282].

Table A1. *Cont.*

Natural Energy Source	Terminology	Definitions
Night	Civil twilight	The period when the Sun is between 0° and −6°; the lowest illuminance ca. 3.4 lx [21].
	Nautical twilight	The period when the Sun is between −6° and −12°; the lowest illuminance ca. 0.008 lx [21].
	Astronomical twilight	The period when the Sun is between −12° and −18°; the lowest illuminance ca. 0.001 lx [21].
	Astronomical night	The period when the Sun is more than −18° below the horizon. This is the period of absence of sunlight within the Earth's atmosphere.
Lunar cycle	Moonlight	Sunlight reflected on the surface of the moon, which due to changing phases and altitude during orbit, results in varied illuminance on the Earth; the maximum possible illuminance is ca. 0.3 lx for a full moon near zenith; typical peak full moon illuminances in mid latitudes are 0.1–0.2 lx [13,47].
Stars, constellations and the Milky Way	Starlight and the Milky Way	The light emitted by stars of the Milky Way, as observed from the Earth during night time [283–285].
Night sky brightness	Radiance/luminance of the night sky	The luminance of a typical clear night sky without light pollution and without airglow is around 200–250 mcd/m^2.
Airglow	Nightglow	A natural dim light caused by the interaction of solar radiation and gases in the upper atmosphere of the Earth, which creates the natural glow of the night. The resulting glow means the night sky is never completely dark [285].
Aurora (Borealis, Australis)	Polar lights	A natural source of light in the sky caused by the collision of charged particles from the Sun (the solar wind) with atmospheric constituents [286]. As shown in Figure A1j.
Living Organisms	Bioluminescence	The light emitted by a living organism caused by a chemical reaction [287]. As shown in Figure A1k–l.
Artificial Energy Source	**Terminology**	**Definitions**
Gas	Gas lighting	A structured system of underground pipes installed in cities to supply gaseous fuel combustion to produce artificial light for the night-time environment. Gas lighting has mainly been replaced with electric lighting, but a few remain as examples of industrial heritage in the urban landscape of cities such as Berlin and London [288–290].
Electric	Electric lighting	A structured system powered by electrical current to produce artificial light at night [290].

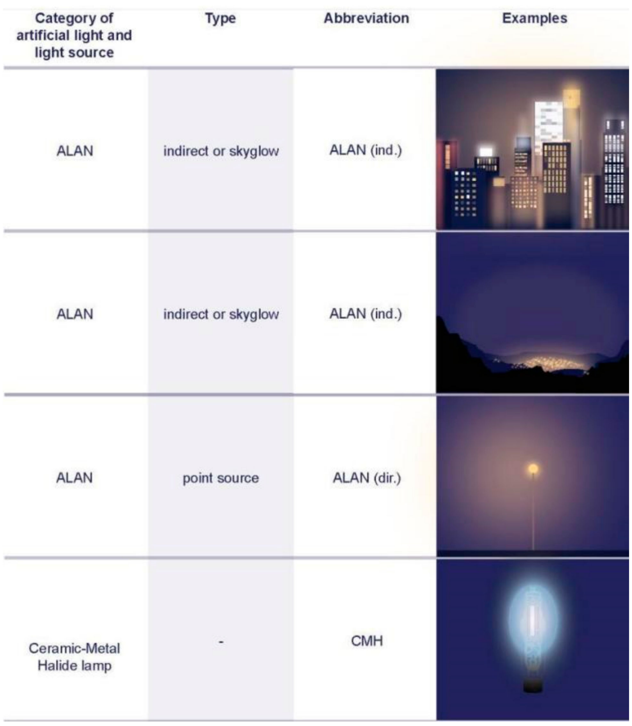
Table A2. Overview of terminologies and definitions of responses to light in living organisms and ecosystems [53,291–299].

Responses	Terminology	Definition
Behavioral response	Diurnality	A behavior occurring during daylight or an organism active during the day and dormant during the night [291,292].
	Nocturnality (or crepuscular)	A behavior occurring during the night or an organism active around sunset, sunrise, or at night, when light conditions are lower compared to daylight [293].
	Migration	The active movement of an organism or group of organisms from one location to a different one. The principle of migration could be periodic (seasonal, with a relative distance, due to changes in climate, temperature, or the availability of resources) or general (the active movement of an organism or group of organisms that may affect the distribution or range of a group of organisms across a landscape [291].
	Navigation	The orientation of a living organism toward a destination (e.g., reaching a breeding area) regardless of its direction, by means other than the recognition of landmarks (e.g., the use of compass orientation) [291].
	Orientation	The ability of an organism to head toward a particular direction without the reference of a landmark [291].
	Phototaxis	The movement or direction of a living organism toward a light source as a behavioral response to changes in illuminance and color in light. This behavior is called positive phototaxis when the living organism is attracted or directed toward the light source, while avoidance or repulsion is called negative phototaxis [294].
Physiological response	Melatonin	A hormone secreted during the dark phase of the day responsible for regulating the sleep/active schedule and the modulation of circadian rhythms that varies between organisms [295].
	Metabolism	Chemical reactions that occur within the cells of an organism that provide energy for biological processes to occur, (e.g., breathing, repairing cells, growth, or digesting food) [291].
Characteristics and processes in plants	Short-day plants	Plants that require short periods of exposure to daylight and long periods of exposure to darkness to initiate the generative phase (less than 8 h/16 h light/dark rhythm) [291].
	Long-day plants	Plants that require long periods of exposure to daylight, with short periods of exposure to darkness, to initiate the generative phase (more than 16 h/8 h light/dark rhythm [296].

Table A2. *Cont.*

Responses	Terminology	Definition
	Photosynthesis	The complex process by which plants transform absorbed light (artificial or natural), carbon dioxide, water, certain inorganic salts, and chlorophyll into energy for growth and survival. An important by-product of this process is O_2 and carbohydrates generated by the conversion of CO_2 and water [297].
Visual response to light	Mesopic vision	The visual sensitivity of a vertebrate to see when exposed to conditions such as twilight at luminances between 0.01 and 3 cd/m^2. Mesopic vision involves both photoreceptors (rods and cones) for scotopic and photopic vision [53,298].
	Photopic vision	The visual sensitivity of a vertebrate to see under lit conditions, such as daylight, which relies on the function of cones (a photoreceptors in the eye's retina) and facilitates perception of colors [298,299].
	Scotopic vision	The visual sensitivity of a vertebrate to perceive its surrounding environment under dim light conditions or during night time, which relies on the function of rods (a photoreceptors in the eye's retina) and facilitates the perception of contrasts without colors [53].

Lighting professionals and ALAN researchers should be able to identify the correct light source by its physical appearance, dimensions, and characteristics (Figure A2) in order to properly perform comprehensible and accurate observational studies and night-time field experiments.



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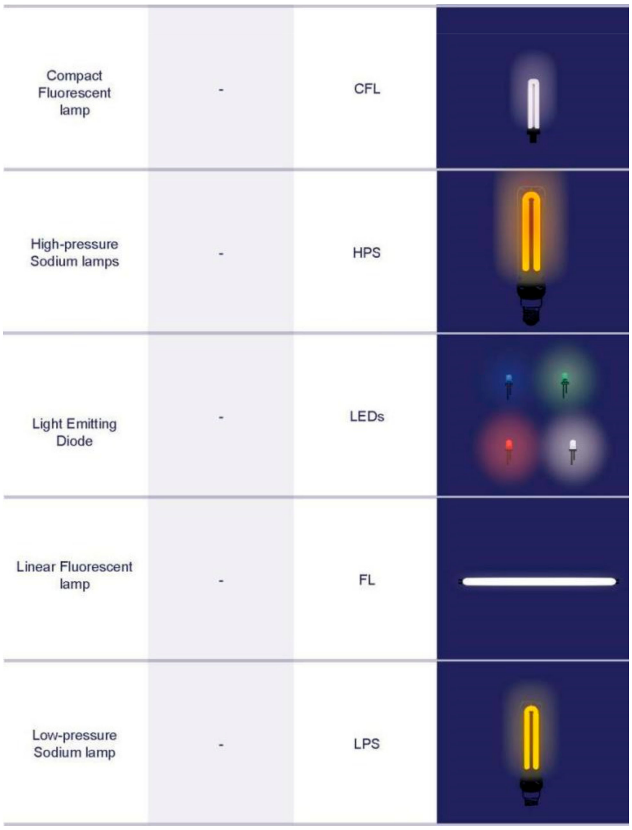

Figure A2. A schematic diagram illustrating the different dimensions of ALAN: ALAN (ind.) in the form of indirect illumination or skyglow in urban and rural areas, ALAN (dir.) in the form of point sources, and six different light sources often used for outdoor night-time illumination: a low-pressure sodium lamp (LPS) and a high-pressure sodium lamp (HPS), a ceramic metal halide lamp (CMH), a compact fluorescent lamp (CFL), light-emitting diodes (LEDs), a linear fluorescent lamp (FL), and a neon and cold cathode lamp. Source: Authors' figure.

Table A3. Overview of various types of electric light sources commonly used in urban settings in the past and present. Source: author's elaboration based on [299–306].

	Definitions
Standard incandescent lamp	An artificial light source where the filament in the lamp is heated to increase the temperature of the filament so that it emits light. A black body radiator with a CCT. Not in common use anymore.
Tungsten-halogen lamp (TH)	An artificial light source with a tungsten filament that is sealed in a transparent housing and filled with a mixture of inert gas and a small amount of halogen to allow higher operating temperatures than standard incandescent lamps. A black body radiator with a CCT of ca. 3000 K. Not in common use anymore.
Linear fluorescent lamp (FL)	An artificial low-pressure mercury gas discharge lamp that uses an electrical current to activate the phosphor coating on the interior of the lamp to glow. (The light that is emitted is rich in short and ultraviolet wavelengths.) FLs are commonly used.
Compact fluorescent lamp (CFL)	An artificial low-pressure mercury gas discharge lamp with a curved or folded tube (smaller in size when compared to fluorescents to fit household light sockets) and an integrated ballast. A CFL uses an electrical current that makes the phosphor coating on the lamp's interior glow. (The light that is emitted is rich in short and ultraviolet wavelengths.) CFLs are commonly used.

Table A3. *Cont.*

	Definitions
Cold cathode (CC) and neon lamp	A gas-discharge source that produces artificial light via electricity emitted from a cathode to ignite mercury vapor through the scattering of kinetic energy. CC and neon lamps are commonly used.
High-pressure mercury vapor lamp (HPM)	An artificial light source in a double compartment bulb (a quartz discharge tube with mercury vapor at high pressure and an outer bulb coated with phosphor). The light that is emitted is rich in short ultraviolet wavelengths and visible light. This light source has been banned due to its negative impact on the environment. Not in common use anymore.
Ceramic metal halide lamp (CMH)	An artificial high-intensity discharge lamp (HID) that uses ceramic material to allow mercury, argon, and metal halide salts to heat at stable but high temperatures to produce light. This light source produces a color rendering index (CRI) and a correlated color temperature (CCT) close to daylight, dependent on the mixture of metal halide salts. CMHs are commonly used.
Low-pressure sodium lamp (LPS)	An artificial low-pressure gas discharge light source that uses sodium in the discharge arc tube to warm the lamp in order to produce light. The light that is emitted is from a narrow band of the spectrum (589 nm), a near-monochromatic amber color unique to sodium lamps. While highly energy efficient and favored around astronomical observatories, it is not in common use anymore and is being phased out in many countries.
High-pressure sodium lamp (HPS)	An artificial high-intensity gas discharge lamp (HID) that produces light through sodium vapor at high pressure. The light that is emitted is broader in spectrum compared to an LPS, with a peak at a wavelength of 586 nm. CCT ca. 2000 K. Still in use but is being phased out.
Light-emitting diode (LED)	An artificial light source that uses a chip of semiconductor material that emits light when an electric current pass through it. It is highly energy efficient, comparable to an LPS, but offers a full spectrum in the visible range and high CRI values. In use and rapidly replacing older light sources, such as LPSs, HPSs, and CMHs. The vast majority of LEDs currently in use for outdoor lighting around the world emit the whole visible spectrum, with peaks of blue wavelengths.

While performing research studies related to artificial lighting and its impact on flora and fauna, it is important to use appropriate metrics/definitions of the units, as presented in Table A4 and in a graphical format in Figure A3. Otherwise, none of the research outcomes can be understood by lighting professionals and integrated into their projects.

Table A4. Overview of radiometric and photometric quantities of light and units. Source [300–306].

Terminology	Definitions
Radiant energy (Qe); luminous energy (Qv)	Energy of electromagnetic radiation, unit J (joule); example, energy of a photon. Luminous energy is the photometric equivalent (i.e., perceived energy referenced to luminosity function); unit (lm s).
Radiant flux (ϕe); luminous flux (ϕ_v)	Radiant energy per time, unit W (watt); example, all light (photons per second) emitted by a lamp in all directions (Figure A3). Luminous flux is the photometric equivalent; unit lm (lumen).
Radiant intensity (Ie); luminous intensity (Iv)	Radiant flux per solid angle; unit W/sr. Luminous intensity is the photometric equivalent; unit cd (candela, lm/sr).
Radiance (Ee); luminance (Ev)	Radiant flux emitted, reflected, transmitted, or received by a surface per solid angle per projected area; unit W/m^{2}sr. Luminance is the photometric equivalent; unit cd/m^2 (lm/m^{2}sr) (Figure A3).
Irradiance (Ee); illuminance (E_v)	Radiant flux received by a surface per area; unit W/m^2; example, horizontal irradiance (Figure A3). Illuminance is the photometric equivalent; unit lx (lm/m^2).
Spectral irradiance (Ee, λ)	Irradiance per unit wavelength (also frequency); unit W/m^{2}nm.
Luminous efficacy of a light source (Ksource)	Ratio of luminous flux to electrical power of a light source; unit lm/W; a measure of how well a light source produces visible light; not to be confused with the luminous efficacy of radiation.
Electrical power of a light source (Pi)	The rated electrical power consumed by a light source (including ballast, driver, control gear, etc., if applicable); unit W (watt).

Table A4. *Cont.*

Terminology	Definitions
Spectral power distribution (SPD)	Distribution of any radiant quantity (radiant energy, radiant flux, radiance, irradiance, etc.) as a function of wavelength, most commonly given in spectral irradiance, ideally provided in nm resolution.
Correlated color temperature (CCT)	Temperature of a Planckian radiator having the chromaticity nearest the chromaticity associated with the given spectral distribution; unit K (kelvin). The CCT can be roughly categorized as warm (<3300 K), neutral (3300–5300 K), or cool (>5300 K) in color appearance.
Color rendering index (CRI)	Measure of the degree to which the psychophysical color of an object illuminated by the test illuminant conforms to that of the same object illuminated by the reference illuminant. The CRI is given in 0–100, with 100 being the most accurate.
Reflectance (ρ)	The effectiveness of a material in reflecting radiant (or luminous) energy.
Flicker	Light source with a temporal change in radiant flux that can, e.g., be perceived as a stroboscopic effect.
Lamp survival factor (LSF) or lamp life	The estimated lifespan of a light source once installed and operating, measured in hours. Operating temperature, frequency of usage and switching, failure of electrical components, the supplied voltage, and vibrations are some factors that may shorten the estimated length of lamp life.
Operating time	The management and control of operating lighting systems for a determined geographical location to specify the hours a luminaire or a lighting system may operate and consume energy (for instance, hourly, daily, weekly, monthly, annually, or seasonal or for cultural events, religious events, or holidays).
Scene setting	The control of illuminance levels and/or color temperatures to set scenes at a determined time for a determined location.
Dimming	The manual or automatic control that manages light output with a programmable timer or sensor installed on-site to provide the gradual decrease of illuminance during a determined period at night or to perform a gradual increase of illuminance levels after dusk.

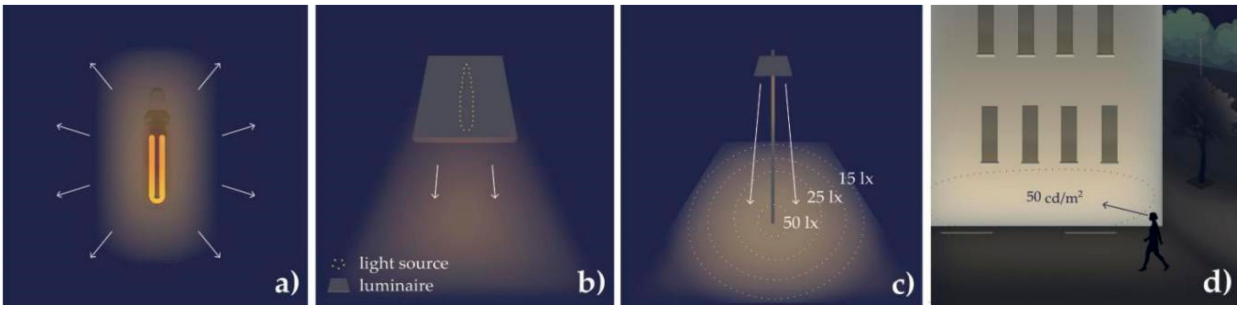

Figure A3. A schematic diagram that illustrates four typical metrics considered by urban lighting professionals: (**a**) luminous flux radiating in all directions, (**b**) luminous flux radiating at a determined area, (**c**) illuminance, and (**d**) luminance. Authors' figure.

For a long time, the lighting industry used the CCT as the only parameter to describe the color appearance of light sources for urban lighting, which can be considered as an insufficient and often-misleading parameter.

There is a different, more important parameter, called the SPD (Figure A4). This parameter can define the energy and wavelengths of an artificial light source that might have a biological impact on living organisms.

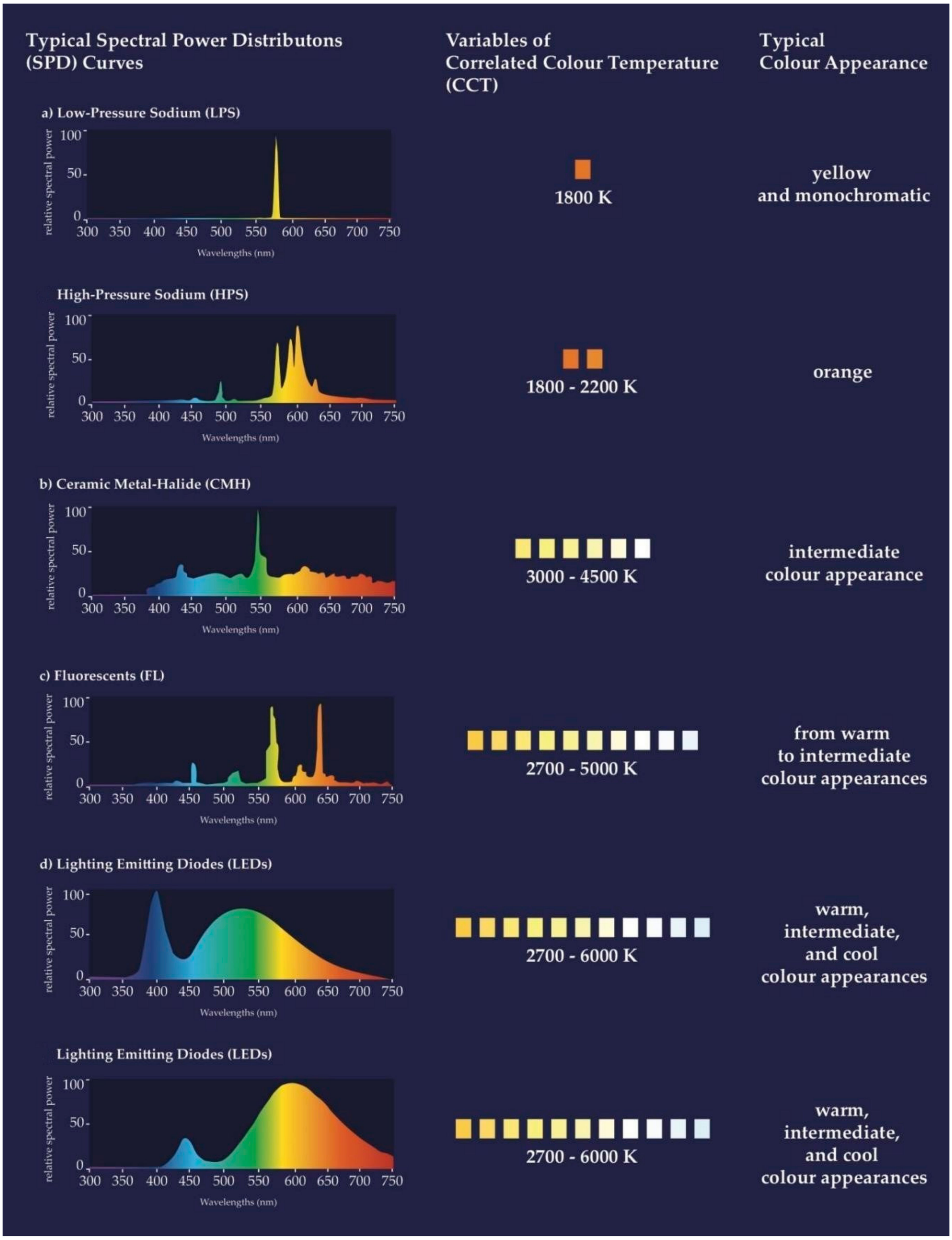

Figure A4. A schematic diagram that illustrates the color appearance of five commonly used types of electric light sources in urban environments: (**a**) low-pressure sodium lamps (LPSs) (amber color appearance) and high-pressure sodium lamps (HPSs) (orange color appearance); (**b**) ceramic metal halide lamps (CMHs), with an intermediate color appearance; (**c**) fluorescent lamps (FLs) with warm to an intermediate color appearance; (**d**) light-emitting diodes (LEDs), which range from warm to intermediate and cool color appearance. Authors' figure.

Over time, many terms and definitions have been established that relate to artificial light at night as a pollutant. Some of them are only used by ALAN researchers and a few of the ones listed in Table A5 are included in lighting standards. This should change in the future so that ULP will be better understood and these aspects can be addressed in night-time projects of illumination.

Table A5. Overview of terminologies and definitions of artificial light at night (ALAN) as a pollutant. Source: author's elaboration based on [6,9,10,307].

Terminology	Definitions
Artificial light at night (ALAN)	A phrase used as a broad term to summarize all forms of artificial lighting (e.g., electric and gas lighting sources), most commonly used to address the unintended consequence of artificial lighting when improperly managed as a form of anthropogenic pollution, which may affect a wide range of environmental processes. ALAN can be described as direct when the source of light is considered a point light source and the parameters of the mentioned source can be modified and as indirect when it addresses the skyglow effect, as it integrates multiple light sources that are reflected from other surfaces.
Astronomical light pollution (ALP)	Mismanaged artificial light that prevents the visibility of starlight and a naturally dark sky.
Ecological light pollution (ELP)	The adverse effect or negative impact of artificial lighting on living organisms and ecosystems.
Glare	The visual and physical discomfort caused by luminance levels that exceed the threshold our eyes can manage.
Light pollution (LP)	The widespread use of artificial illumination in the night-time environment and the unwanted consequence of improperly managed and poorly controlled lighting properties of artificial light sources and luminaires. Artificial light that is polluting the natural light. Light pollution occurs in four ways, skyglow, glare, light trespass, and clutter, all of which prevent visibility of the naturally dark sky and stars and is defined as astronomical light pollution. Light pollution also has an adverse effect on aquatic and terrestrial ecosystems and living organisms and is defined as ecological light pollution.
Light trespass	Objectionable light from an artificial light source that intrudes into indoor settings and private property, illuminating spaces not meant to be illuminated. The term "light trespass" has been commonly used to describe the intrusion of light into settings where it is not meant to be, such as gardens or natural habitats.
Visual light clutter	Visual light clutter in the urban environment at night is defined as the state in which too many items lead to a degradation of the performance of a visual task at night.
Obtrusive light	The quantitative, directional, or spectral properties in light, which can cause visual discomfort and distraction and also hinder the perception of nearby environments.
Over-illumination	The presence of unnecessary artificial lighting caused by excessive brightness, too many luminaires, and the varied coloration of artificial light from different sources, which blends together and forms an unnatural gleam.
Skyglow	Glow from light radiated upward that is then scattered within the atmosphere and diverted back to the Earth. It often results in a diffuse light dome above densely populated areas and extends across landscapes. A consequence of luminaires improperly directing light upward toward the sky or from reflected light. Skyglow depends on the weather and atmospheric conditions. Skyglow used to have orange color from LPSs and HPSs, but today, skyglow can have a cool, white appearance from LEDs.

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