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Better, not more, lighting: Policies in urban areas towards environmentally-sound illumination of historical stone buildings that also halts biological colonization

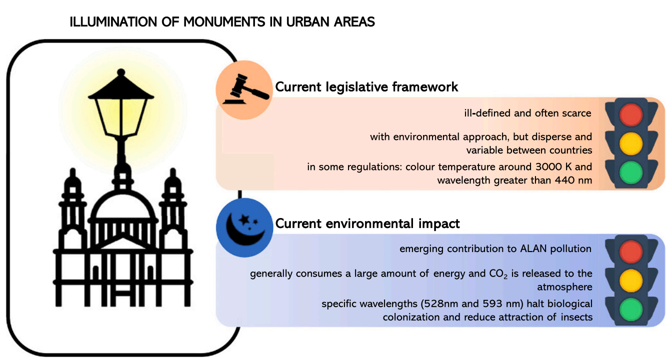
Anxo Méndez [a,b], Beatriz Prieto [a,b], Josep M. Aguirre i Font [c], Patricia Sanmartín [a,d,*]

[a] GEMAP (GI-1243), Departamento de Edafoloxía e Química Agrícola, Facultade de Farmacia, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain
[b] CISPAC, Cidade da Cultura, Santiago de Compostela, Spain
[c] Departament de Dret Públic, Universitat de Girona, 17003 Girona, Spain
[d] CRETUS, Universidade de Santiago de Compostela, Santiago de Compostela, Spain

HIGHLIGHTS

- Light pollution policies in European countries are ill-defined and generally scarce.
- Illumination of monuments is an emerging contribution to ALAN pollution.
- ALAN pollution caused by illumination of monuments is defined.
- Illumination policies could help to reduce biodeterioration and protect biodiversity.

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic or Artificial light at night (ALAN) pollution, or more simply light pollution, is an issue of increasing concern to the general public, as well as to scientists and politicians. However, although advances have been made in terms of scientific knowledge, these advances have not been fully transferred to or considered by politicians. In addition, illumination of stone monuments in urban areas is an emerging contribution to ALAN pollution that has scarcely been considered to date. This paper presents a literature review of the topic of light pollution and related policies, including a bibliometric analysis of studies published between 2020 and 2022. The prevailing legislation in Europe regarding the regulation of outdoor lighting, which emphasises the complexity of controlling light pollution, is summarised and the regulation of monumental lighting in Spain is discussed. Findings concerning the impact of ALAN on biodiversity in urban areas, and the promising biostatic effect of ornamental lighting (halting biological colonization on stone monuments, mainly caused by algae and

* Corresponding author at: GEMAP (GI-1243), Departamento de Edafoloxía e Química Agrícola, Facultade de Farmacia, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain.
E-mail address: patricia.sanmartin@usc.es (P. Sanmartín).

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cyanobacteria) are described. Finally, trends in monument illumination and policymaking towards environmentally sustainable management are considered.

1. Introduction

Until the introduction of public lighting in the 17th century, outdoor illumination of building façades, with flame lanterns in many European cities, was the responsibility of private citizens (Schivelbusch, 1995). The illumination served both to enhance the beauty of buildings at night and to ensure visibility and safety in the street, functions that remain relevant today (Žák and Vodráčková, 2016). Since their introduction, light infrastructures have been managed by public authorities, with control increasing with the popularity of ornamental illumination during the 18th and 19th centuries (Seitinger, 2014). Public lighting has gradually evolved from the original gas lamps to electric lamps (Schivelbusch, 1995).

Illumination of outdoor monuments should aim to highlight natural colours and shapes, and it thus often bathes monuments in upward and lateral directions, thereby contributing to the phenomenon of artificial light at night (ALAN) pollution or light pollution (the main negative effect). The terms light pollution and ALAN pollution are almost synonymous; however, the former can also include poorly implemented daytime lighting, and the latter is less commonly used and more closely linked to biological effects. Light pollution is rather ill-defined, varies between different fields and is subject to debate, as will be explained in more detail below. For our purpose and considering built monuments, and also taking into account the suggestions of various authors (ILP, 2011; Aubé, 2015; Żagan and Skarżyński, 2017; Stone, 2019), ALAN pollution derived from monument illumination can be defined as “the ornamental lighting on monuments that is not being efficiently or completely utilized and exceeds the limits of the object and scatters to the atmosphere (often because is pointed outwards or upwards), causing artificial ambient brightness that has an overall negative effect on the environment”. According to a study of about ten years ago (Mohar et al., 2014), 60 %–80 % of the ornamental lighting on monuments is emitted to the sky and the surroundings, not reaching the monument façade, and at that time it was estimated that it would give rise to the 5 %–20 % of total ALAN pollution in developed countries.

Light pollution (whether ornamental or for other uses) can affect all ecosystems, both terrestrial and aquatic, on the planet. In Europe, light pollution is increasing at a rate of 2 % to 10 % each year, reflecting the lack of sustainability of the outdoor lighting model used in various countries (Hölker et al., 2010; Kyba et al., 2014, 2017). The wide variety of definitions of light pollution, derived from the different unwanted side-effects of ALAN and considered in various research fields, has been pointed out (Schulte-Römer et al., 2019). This variety also leads to a diversity of views and findings that are difficult for policymakers to combine in cohesive legislation. Astronomers consider ALAN detrimental regarding observation of the night sky (Smith, 2009), and biologists consider ALAN harmful to nocturnal species and ecosystems (Gaston et al., 2015). Nocturnal animals in urban and other artificially lit areas can be attracted towards ALAN and become disorientated, affecting foraging, reproduction and other behaviours, resulting in disruption of interspecific relationships, with serious implications for community ecology (Longcore and Rich, 2004). Humans are also affected, as disruption of the natural circadian rhythm is linked to various health problems such as cancer, Alzheimer’s disease, depressive disorder, atherosclerosis and cardiovascular diseases (Menéndez-Velázquez et al., 2022). Around 55 % of the world’s population already lives in urban areas and this figure is expected to increase to 68 % by 2050 (Katabaro et al., 2022). Individuals exposed to high levels of ALAN are more likely to have poorer health, with disrupted sleeping patterns and increased levels of stress and anxiety leading to hormonal and metabolic changes (Widmer et al., 2022). Plants and other photosynthetic organisms are also impacted by ALAN, with negative effects on natural primary production and photosynthetic performance and signs of metabolic stress observed (Singhal et al., 2019).

In stone-built heritage, the impact of ornamental ALAN not only affects the surrounding environment, but also the building façades themselves. Artificial light can directly influence the biological colonization of these sites, in particular driving biofouling by phototrophic organisms (Sanmartín et al., 2017, 2021; Zafra-Castro, 2020; Sanmartín, 2021). However, the issues concerning heritage conservation in that sense are overlooked by current legislation on outdoor lighting and light pollution, probably due to the lack of knowledge about the concrete impact of ornamental lighting at night on the potential biodeterioration risks.

Illumination of monuments should focus on the yellow part of the spectrum (between 565 nm and 625 nm wavelengths, in a broad sense) and use as little blue light (between 400 nm and 500 nm wavelengths, in a broad sense) as possible. In other words, the lighting should not emit wavelengths less than 500 nm and have low emission above 650 nm, to minimize the impact on animals, humans and plants. Bluish light causes more light pollution than yellowish or reddish light because, according to Rayleigh’s law, shorter wavelengths (like blue light) scatter exponentially more than longer wavelengths (like yellow and red light). A serious shortcoming of the regulations regarding the lights used to illuminate cultural monuments is that they do not focus on restricting use to the yellow part of the spectrum (i.e. less than 3300 K–2700 K and main peak wavelength around 580 nm) or limiting to less than 10 %–15 % the share of blue light (with a main peak around 440–450 nm). Note that colour temperature in degrees kelvin (K) increases with the proportion of the blue part of the spectrum the emitted light contains; e.g. a white light with a high percentage of blue colour can reach a colour temperature of 6500 K.

The aim of this review is to provide an up-to-date view on policies and legislation of outdoor illumination regarding historical stone buildings and light pollution, as well as the associated environmental impact. Thus, following on from this introductory Section 1, the paper is structured as follows. Section 2 presents a literature review of the topic on light pollution and policies, including a bibliometric analysis of studies published in the past three years (2020–2022). Section 3 outlines the prevailing legislative framework in Europe in regard to the regulation of outdoor lighting, emphasising the complexity of regulating light pollution and discussing how monumental lighting is regulated in Spain. Spain is a pioneer in this regard, with the first legislation appearing in 1988, and it also has the challenge of protecting its cultural heritage, one of the most extensive in the world. Spain is therefore used as an example for studying the regulation of lighting historical stone building. Section 4 deals with the impact of ALAN on biodiversity in urban areas, and the promising biostatic effect (halting biological colonization, mainly by algae and cyanobacteria) of ornamental lighting for the conservation of stone monuments. Finally, Section 5 concludes with an analysis of trends in monument illumination and policymaking towards environmentally sustainable management of the lighting.

2. Previous research reviews on ALAN pollution

In a recent review on literature regarding light pollution (Rodrigo-Comino et al., 2021), most of the 621 papers (published between 2003 and 2019) considered involve light pollution in general, the impact of light pollution on ecosystems and human health, and the economic implications. However, policies regulating light pollution were not considered, probably because very few of the 621 papers address this topic. Thus, it seems that there is little or no connection between

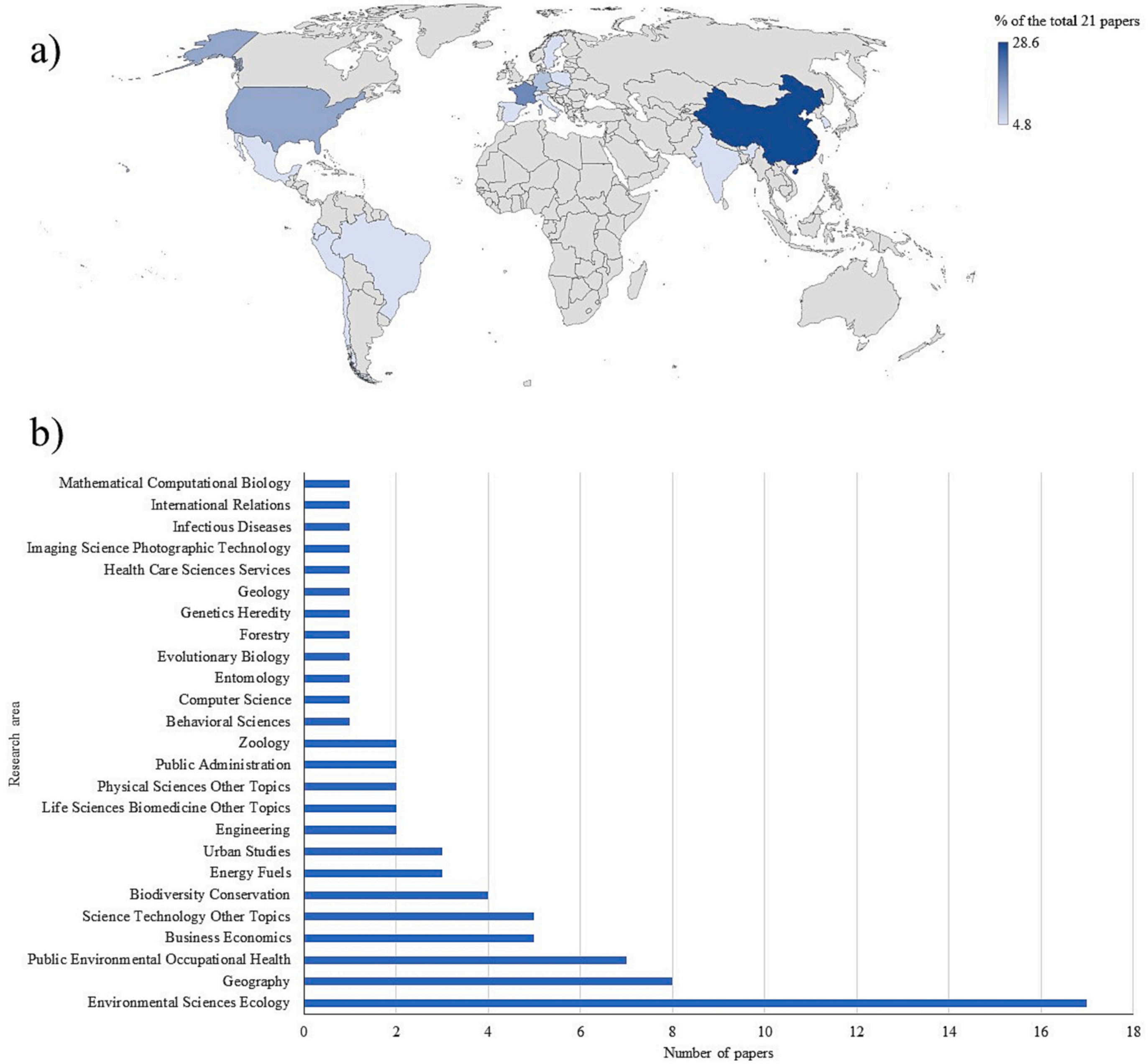

Fig. 1. a) Distribution of the 21 papers by research area, and b) contribution (in %) of the 21 papers by country. In both cases they show the results found between 1 January 2020 and the 31 October 2022.

research and policies or that the knowledge produced by research does not lead to the development of sustainable management plans.

In the present study, a new review was conducted considering literature published between 1 January 2020 and 31 October 2022, by using the ISI Web of Science. Use of the search term "light pollution" yielded a total of 821 publications. Refining the search with the term "policies" produced only 21 papers. Fig. 1a shows the distribution of the 21 papers by research area. Although most are included in the Environmental Science category, those included in the Urban studies (3), Public administration (2) and Business economy (4) categories were those that focused most on policies involving outdoor ornamental illumination for historical stone buildings. In Fig. 1b the distribution of those 21 papers is shown by country. Most of the studies reported in the papers were conducted in China (28.6 %), followed by France (19.0 %) and the USA (14.3 %). For each of the other countries, only one paper was published in the study period, except Germany with 2 papers.

A search within the abovementioned 821 papers was conducted using different terms to select those papers focused on monumental illumination. Four papers appear under the topic of "cultural heritage", but none of these were included in the papers concerning policies. Three of those four papers deal with the dark night as part of the intangible cultural heritage and one concerns tangible built heritage. In the latter, Kobav et al. (2021) proposed a sustainable exterior lighting design for cultural heritage buildings, according to the prevailing legislation concerning light pollution in Slovenia, which is based on general recommendations for the sustainable illumination of cultural heritage objects; however, these recommendations are not reported in the paper. Replacement of the term "cultural heritage" with "monument" produced only one paper. This paper concerns the impact on bats of the illumination of a historic building inside a Natura 2000 national park in Poland (Zielinska-Dabkowska et al., 2021), focusing on the biodiversity conservation policies in the national park but not on policies regarding illumination. Use of the term "ornamental" yielded only two papers, both about ornamental vegetation and not built construction. Use of the term "façade" produced six papers, which deal with the contribution of the illumination of façades to light pollution, but do not include the term "policies".

Among the abovementioned 21 reviewed papers concerning light pollution policies, the paper by Galindo et al. (2022) is the only one that addresses current policies regarding public lighting services. Most of these policies are related to energy efficiency but they also include environmental policies used as guidelines to establish the technical specifications for luminaries in order to reduce light pollution. All of the other articles suggest the need to generate policies to reduce outdoor light pollution because of its deleterious effects (e.g. Argentiero et al., 2021; Vaz et al., 2021; Yu et al., 2022), and they emphasize the importance of establishing plans such as those existing in relation to air, noise, water and soil (Gonzalez-Madrigal et al., 2020). In this respect, Jagerbrand (2020) suggests that exterior lighting should contribute to, and not counteract, the sustainable development of the planet, pointing out that the interactions between sustainable development and energy performance can be used to produce more efficient policies for decision-making processes regarding exterior lighting. Policies mitigating light pollution have been applied in Japan and the USA since the 1990s, and their success has resulted in the sustainable development of ecology and environment in and around urban domains (Mu et al., 2021).

Some authors suggest measures to resolve the impacts of light pollution. Thus, Kaushik et al. (2022) pointed out some adaptive measures: i) increasing awareness in both individuals and communities, ii) minimizing excess light through technical improvements, iii) making changes in the policies, as the luminance limits established by the International Commission on Illumination (CIE) are not effective for regulating light trespass, iv) minimizing the ecological impact by reducing light trespass. Hu et al. (2021) and Sordello et al. (2022) proposed implementing (in the context of green and blue infrastructure policies) a dark infrastructure to prevent landscape fragmentation due to the impact of artificial light on biodiversity, and Lapostolle and Challeat (2021) point out the convenience, in terms of both preserving biodiversity and fostering the energy transition of planning policies, of taking advantage of darkness as a resource for sustainable development.

Although reducing light intensity and using modern lighting technologies are effective measures for reducing light pollution, air pollution (mainly derived from aerosols) should also be considered as this also increases the brightness of the night sky (Kocifaj and Barentine, 2021).

Kim and Kim (2021) highlight the importance of predicting light pollution in the early stages of building design in order to control light pollution. The "light pollution Prevention Act" in Korea classifies areas where light management is envisaged in categories ranging from E1 (Green areas for conservation, darkest areas) to E4 (semi-industrial and commercial areas, brightest areas) and indicating the permissible luminance values for lighting spaces, advertisements and decorative lighting, thus enabling prediction methodologies to be developed.

One point underlying all the articles is that future lighting policies should be developed within a collaborative framework involving a transdisciplinary process; e.g. Pérez Vega et al. (2021) suggest including environmental experts, lighting professionals and experts from other fields.

3. Legislative framework in Europe: the Spanish example

3.1. Current legislation for ALAN from monumental illumination

As already indicated, light pollution has significant impacts on safety, human health and the environment and in recent years there has been some debate among scientists regarding its definition and measurement (Schulte-Römer et al., 2019; Jägerbrand et al., 2022). This open debate is reflected in the regulations implemented in various European countries, which have adopted different strategies and legal means of addressing the problem of light pollution (Morgan-Taylor, 2015). In Croatia, Germany, France, Spain and Malta, light pollution is directly act upon, from the perspective of energy saving for environmental and economic reasons. Regarding the illumination of public buildings, Italy and Spain have implemented some policies aimed at lowering ornamental ALAN, such as aiming the lights downwards when illuminating building façades and other monuments, reducing the time during which monuments are illuminated, using the minimum intensity of light, reducing the colour temperature of light and shielding the luminaire to restrict the lighting to the shape of the object (Kyba et al., 2018; Falchi et al., 2019). Also in Italy, illumination of buildings in an upward direction is forbidden (Zitelli et al., 2001), to prevent direct light pollution, and Bavarian state law prohibits lighting building façades (churches, castles and administrative buildings) between 23:00 and sunrise (Schroer et al., 2020). However, Finland, Hungary and Slovakia do not have any designated legislative act that addresses light pollution, although provisions from other legislative acts or even non-binding guidelines or instructions from the Belgian and Polish governments are applied (Ministry of the Environment of the Czech Republic, 2022).

Another good example of the disperse actions can be found in the EU. Thus, although the EU promotes the study of light pollution in its EU Action Plan "Zero pollution for air, water and soil" (European Commission (EC), 2021), it has been unable to approve a global regulation on the matter, which was only addressed peripherally in the eco-design requirements for the marketing of lamps in the repealed Commission Regulation (EC) No 245/2009 of 18 March 2009 (European Commission (EC), 2009) and in the current EU green public procurement criteria for road lighting and traffic signs (Donatello et al., 2019). In the case of Spain, as an example of a European country, the fight against light pollution, which has its origins in the pioneering Law 31/1988, of 31 October, on the Protection of the Astronomical Quality of the Observatories of the Instituto de Astrofísica de Canarias (Heading of the Spanish State, 1988), is addressed through different jurisdictional titles: those linked to environmental protection (article 149.1.23 EC) and those linked to the regulation of economic or energy activity (articles 149.1.13 EC and 149.1.25 EC). This has enabled a double-headed approach; on the one hand, environmental regulation with state regulations that have established the basic conditions in this area and autonomous regional regulations that have developed additional rules for the protection of light pollution; and on the other hand, economic or energy-related regulation by the state.

From an environmental perspective, the fight against light pollution has given rise to diverse regulations, depending on the autonomous community, but which share common bases established in the State Law 34/2007, of 15 November, on air quality and protection of the atmosphere (Heading of the Spanish State, 2007), which defines "light pollution" as any artificial glow that "alters the natural conditions of night-time hours and hinders astronomical observations" and establishes common objectives for all public administrations in the fight against light pollution in its fourth additional provision:

"a) To promote efficient use of outdoor lighting, without detriment to the safety it should provide for pedestrians, vehicles and property.

b) To preserve as much as possible the natural conditions of night-time hours for the benefit of fauna, flora and ecosystems in general.

c) To prevent, minimize and correct the effects of light pollution in the night sky, and in particular in the vicinity of astronomical observatories working in the visible spectrum.

d) To reduce light intrusion in areas other than those intended to be illuminated, mainly in natural environments and inside buildings".

Also from an environmental perspective, the following autonomous regions have legislation on light pollution: the Canary Islands (through a state law), Catalonia, the Balearic Islands, Navarre, Cantabria, Andalusia, Castile and Leon and Extremadura (Ríos, 2008; García Gil et al., 2012). As in the regulations in other states, diverse approaches to the problem are also taken, ranging from individual laws to regulations that fall within the framework of environmental assessment legislation.

Table 1
Average illuminance levels for ornamental lighting as a function of the type of material in the illuminated construction and the level of illumination of the surroundings. The correction factors to be applied according to the type of lamp and the degree of fouling. Extracted and modified from ITC-EA-02 (Ministry of Industry, Trade and Tourism, 2008) are also shown.

Type of material in the illuminated construction	Average illuminance levels (Lux)			Multiplying coefficients for correction			
	Lighting in surroundings			Correction for lamp type		Correction for fouling degree	
	Low	Medium	High	LED and MH	HPS and LPS	Dirty	Very dirty
Light-coloured stone, light marble	20	30	60	1.0	0.9	3.0	5.0
Medium-coloured stone, cement, coloured light marble	40	60	120	1.1	1.0	2.5	5.0
Dark-coloured stone, grey granite, dark marble	100	150	300	1.0	1.1	2.0	3.0
Light yellow brick	35	50	100	1.2	0.9	2.5	5.0
Light brown brick	40	60	120	1.2	0.9	2.0	4.0
Dark brown brick, pink granite	55	80	160	1.3	1.0	2.0	4.0
Red brick	100	150	300	1.3	1.0	2.0	3.0
Dark brick	120	180	360	1.3	1.2	1.5	2.0
Architectural concrete	60	100	200	1.3	1.2	1.5	2.0

However, in Spanish regulations the most specific measures designed to combat light pollution are not found in any environmental regulations, but rather in the Regulation on energy efficiency in outdoor lighting installations and its complementary technical instructions EA-01 to EA-07 (approved by Royal Decree 1890/2008 of 14 November), which establishes the technical criteria for outdoor luminaires, determining factors for preventing or accelerating light pollution. These regulations have dated rapidly with the proliferation of LED technology, which has replaced traditional light bulbs and has made it possible to augment lighting at less cost, but also increasing light pollution (García Gil et al., 2022). In fact, as the authors point out, "the most efficient LED lamps, the 4000 K white ones, are also those with the highest radiation below 500 nm. Therefore, they are potentially the most polluting". As explained in the Section 1, a higher proportion of the blue component will increase the colour temperature of the lamp, making it more energy efficient but also more polluting. The current trend in Spanish and European regulations is to use lamps of around 3000 K and below 4000 K, avoiding spectra with radiances below 440 nm (blue light).

The existing regulation was intended to be reformulated with the "Regulation on energy saving and efficiency and reduction of light pollution in outdoor lighting installations and its complementary technical instructions" (Ministry of Industry, Trade and Tourism and the Ministry for Ecological Transition and the Demographic Challenge, 2021), which began to be processed in 2022 and remains paralysed at the time of writing this paper. The initially high expectations of the draft regulation have led to frustration regarding its content, which not only fails to establish limits and objective values for the control of light pollution, but also directly favours an increase in outdoor lighting by establishing lighting obligations that have not existed until now, e.g. the compulsory lighting of all roundabouts and an area of 200 m along their exits (Malón et al., 2022). In this regard, administrative paralysis of the new regulation has made it necessary to advance some of the provisions in the recently published Royal Decree-Law 18/2022 of 18 October, issued in the context of the crisis caused by Russia's invasion of Ukraine and its consequences on international energy markets. The new regulation incorporates new lighting technologies that were not contemplated in 2008, increases the energy efficiency requirements for outdoor lighting installations and makes the energy label more visible to citizens.

Table 2
Reflection factor for some materials. Extracted and modified from ITC-EA-02 (Ministry of Industry, Trade and Tourism, 2008).

Material[a]	Reflection factor (ρ)
Grey granite	0.10–0.15
Red brick	0.15
Dark marble	0.15
Dark-coloured stone	0.15
Brown brick	0.3
Pink granite	0.3
Clear-coloured marble	0.3
Medium stone	0.3
Cement	0.3–0.4
Light yellow brick	0.35
Light-coloured tone	0.5
Light marble	0.50–0.60

[a] All materials considered clean.

Focusing on the regulation of ornamental lighting concerning this review article, at state level it is specified in the non-binding technical guide for the practical application of the provisions of the Regulation and its Supplementary Technical Instructions provided for in the single additional provision of Royal Decree 1890/2008, of 14 November. This guide, in its different versions (Ministry of Industry, Trade and Tourism, 2008), regulates in its Complementary Technical Instruction (abbreviated to ITC in Spanish) EA-02 on lighting levels for ornamental lighting that includes façades of buildings and monuments, as well as statues, walls and fountains; it also includes landscaping of rivers and riverbanks and incorporates a practical chart analysed in the following subsection.

Finally, at the regional level, the ornamental lighting regulations developed through the regulations of some autonomous communities, such as Catalonia (Decree 190/2015), Navarre (Decree 199/2007), Cantabria (Decree 48/2010), Andalusia (Decree 357/2010), and the Balearics (draft regulation currently being processed). These regulations control aspects related to the type of lamps, their installation, maximum lighting levels, switching off at night, and the municipal competence regarding determination of the illuminated assets or their administrative authorisation.

3.2. Practical chart regarding the illumination of stone monuments in urban areas

The Complementary Technical Instruction ITC-EA-02, in the aforementioned Spanish Royal Decree 1890/2008 of 14 November, includes a chart or summary with practical guidelines (Table 1) defining the minimum mean illuminance values (in Lux) according to the colour (light, dark, pink, red, brown, yellow or grey) and type of construction material (marble, cement, granite, brick, also stone in general) being illuminated and the level of illumination (low, medium and high) of the surroundings, along with the correction factors to be applied according to the type of lamp (light emitting diode, LED; metal halide, MH; high-pressure sodium vapour, HPS; and low-pressure sodium vapour, LPS) and the degree of fouling due to exposure to environmental conditions (dirty and very dirty).

However, despite its apparent usefulness, Table 1 lacks some relevant information, since it does not indicate the thresholds for considering the surrounding illumination as low, moderate or high. Nor does it specify what should be considered dirty or very dirty in relation to the illuminated surface. In addition, the chart covers the use of all types of lamp technology, ranging from LED to LPS. This is influenced by the fact that the instruction is now fifteen years old and has not yet been updated. Today the global trend is towards the exclusive use of LEDs. LPS and HPS lamps are the oldest styles and contain metals such as mercury (Rodrigues et al., 2011) and have a low efficiency and lifespan relative to MH and LED lamps (Stone et al., 2015; Sadeghian, 2018). Their replacement by MH lamps has led to lower maintenance costs and higher energy efficiency. However, use of MH lamps still requires the consumption of large amounts of energy and leads to the release of large amounts of CO_2 to fulfil the requirements of most streetlight illumination. The use of LEDs reduces the amount of energy required by up to between one third and one half (Aoyama and Yachi, 2008), with a low maintenance cost and a compact volume (Vu et al., 2017), suitable for illuminating monuments (Zafra-Castro, 2020).

One aspect that can be extracted from Table 1 is that the amount of illumination required depends on how dark the surface is (owing to the reflection factor, Table 2). For instance, illumination proposed for dark brick is six times greater than that for light marble and twice as much as that proposed for concrete. In addition, ornamental illumination in a moderately illuminated environment must be 1.5 times higher and in strongly illuminated surroundings it must be 3 times higher than in weakly illuminated surrounding environment. Likewise, illumination of buildings in areas with high surrounding illumination should be twice than in moderately illuminated surroundings. In addition, the correction factors for the type of lamp are always higher (with a difference of between 0.1 and 0.3, with the highest corresponding to chromatics in brown, red, yellow-coloured illuminated materials) for LED and MH than for HPS and LPS, except in the case of dark-coloured stone, grey granite and dark marble. In this respect, LED and MH lamps have a lower colour temperature, with a lower blue component and a higher yellow component, than HPS and LPS, which leads to loss of intensity when illuminating surfaces with a reddish-yellow component (such as pink granite and red brick) but to strong illumination of grey-blackish surfaces (such as grey granite and dark marble). Finally, the presence of fouling decreases the reflection factor (Table 2), darkening the illuminated surface, so that illumination of between 1.5 and 3 times higher is required for dirty surfaces and of between 2 and 5 higher for very dirty surfaces. Fouling has less impact on dark brick and architectural concrete and a greater impact on light-coloured stone and light marble.

4. Biological impacts

4.1. Biodiversity and ALAN

The International Union for Conservation of Nature (IUCN) has warned that the extinction of animal and plant species has never occurred as rapidly as at present, and the rate is increasing annually. ALAN pollution is exacerbating the rate of extinction, being listed among ten main factors endangering nocturnal animal biodiversity. Many animal species are dormant during the daytime and become more active at night, especially in urban areas (Hölker et al., 2010). Some nocturnal animals are attracted by light (positive phototaxis), and some are repelled by it (negative phototaxis). This effect is species-specific, and e.g. some bat species have started to go towards light to feed while many other bat species tend to avoid lamps (see e.g. Salinas-Ramos et al., 2020). Animals caught in light can be killed by direct collision with the lit structures, predated by other organisms or become exhausted and run out of time for feeding, reproduction and migration due to the disorientation (Méndez et al., 2022), while those avoiding light are losing their natural habitats. ALAN pollution also interferes with the moonlight and starlight used by many animals for navigation (Barta et al., 2014). Moonlight is highly polarized, and insects like beetles have receptors that detect that polarization for orientation at night (Dacke, 2014). Likewise, moonlight serves as a major environmental cue for aquatic organisms, for example entraining diel vertical migration of zooplankton at depths down to 50 m (Last et al., 2016).

Scotobiology or the biology of darkness has been defined as the study of the biological need for periods of darkness (Dick, 2014). Scotobiological studies allow to determine the ecological limits for ALAN according biological and behavioural drivers, a task complicated by the wide range of tolerance of different nocturnal life forms, with five critical lighting attributes identified: the amount of illumination, the extent of the illuminated area, the glare, the spectrum of the emitted light, and the duration of the illumination (Dick, 2021).

Hölker et al. (2021) have identified eleven main research questions regarding how light pollution affects biodiversity, ranging from genes to ecosystems. According to these authors, the impact of ALAN on the multiple levels of biodiversity (genes and cells, individuals, populations, communities, ecosystems and landscapes) is largely unknown, making it difficult to design effective mitigation measures at present. In addition, photobiological responses to ALAN have not been adequately described for most species. For example, although the insects are probably the group of organisms that have been most widely studied in this respect, and half of the one million species of insects that have been described are nocturnal, information about the spectral sensitivity of insect photoreceptors is only available for 221 species (less than 0.03 %) (Hölker et al., 2021). Moreover, the lack of knowledge affects the species directly impacted by ALAN but also those indirectly affected throughout interactions with the former in ecological communities. In addition, such heterogeneous responses to ALAN among and within species groups can alter distribution patterns and create novel communities (Voigt et al., 2021), with potential concomitant effects on ecosystem functions such as mineralization, pollination and seed dispersal. Furthermore, responses to light colour and intensity are not uniform across taxonomic groups (Burt et al., 2023). In relation to outdoor lighting policies, species and landscapes with special protection status, e.g. migrating birds and Natura 2000 sites, are generally only considered in existing regulations regarding ALAN (Schroer et al., 2020).

ALAN pollution, especially that caused by blue light, can directly disrupt melatonin (sleep hormone) synthesis, even at low illumination levels; it can also have other negative impacts on the circadian (day-night) rhythm, which balances body temperature and blood pressure, and other physiological processes, in both people and animals (e.g. Cajochen et al., 2005). Melatonin is present in almost all life forms and has functioned as a cellular protectant against free radicals and oxidation for ~3.6 billion years, and is secretion at night is essential (Tan et al., 1993). Melatonin may promote regeneration of cells or tissues and prevent carcinogenic alterations (Li et al., 2017).

Insects constitute a high proportion of nocturnal species (Baz et al., 2022) and are essential organisms in the ecosystem because they have many important ecological roles. However, insect numbers have declined significantly, especially in urban areas, because of ALAN (Owens and Lewis, 2018). The insect orders Diptera, Hymenoptera, Lepidoptera and Coleoptera have been found to be the most strongly impacted by ALAN in urban areas of Chongqing (southwest China), i.e. urban parks (Liu, 2019), and Santiago de Compostela (northwest Spain), i.e. the historical centre (Méndez et al., 2022). Selection of specific wavelengths (528 nm and 593 nm in the green and amber part of the spectrum) by ALAN has been observed to reduce both the abundance and diversity of insects attracted to the light source, with similar numbers captured as in the unilluminated area (Méndez et al., 2022).

The spread of ALAN within ecosystems varies according to the medium and is not the same in air as in water. In this respect, more studies have been conducted in aerial environments than in aquatic environments. Indeed, according to Hölker et al. (2021) most research regarding the effects of ALAN on biodiversity has focused on a very limited range of ecosystems: natural terrestrial systems in temperate and developed regions. An interesting case study in the rivers and riverbanks integrated in the urban fabric, where it would be of high interest to capture the impact of ALAN, is that of the *El Muelle de la Compañía Río Tinto* (The Rio Tinto Company Pier) in Huelva, southwest Spain. The pier is an example of 19th century industrial heritage located near a biosphere reservoir (UNESCO Odiel Marshlands Biosphere Reserve), and it is illuminated by an impressive lighting display (completed in 2020). However, doubts

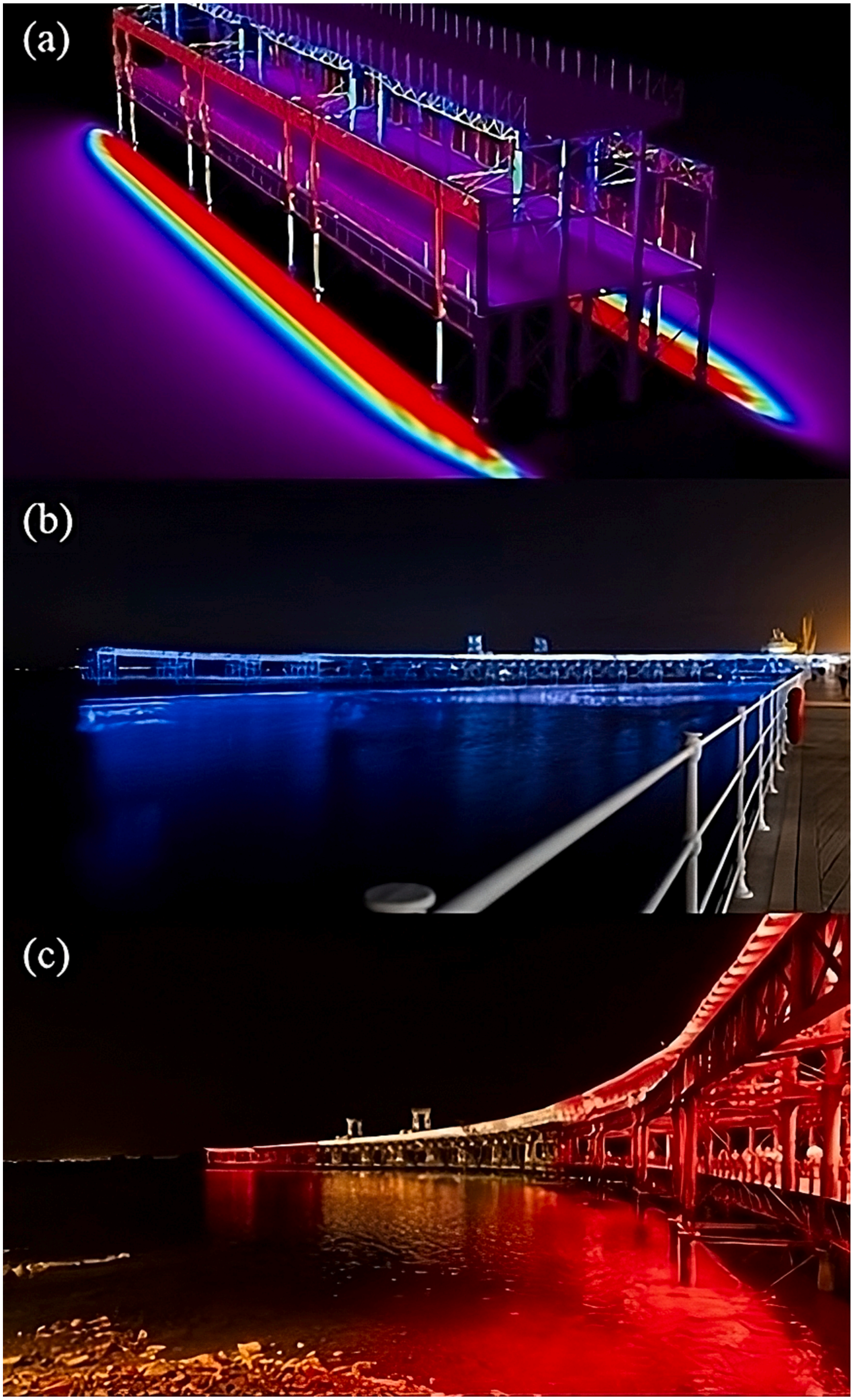

Fig. 2. (a) Rendered image of a section of *El Muelle de la Compañía Rio Tinto* (Rio Tinto Company Pier) in the Odiel estuary (Huelva, Spain), (b) photograph of the pier illuminated in blue and (c) photograph of the pier illuminated in red. All images are extracted from https://www.huelvainformacion.es/.

have emerged that have not yet been resolved about the impact of the lighting on the biodiversity in the surroundings. The illumination system comprises 700 LED spotlights with a wide range of colours, ranging from warm and cold white, to red, green and blue coloured light (Carrasco, 2019). Fig. 2 shows a rendered (synthesised) image of the lighting system, as well as photographs of the lighting in red and blue, the latter being the most frequently used to illuminate the pier. As it can be seen in the images, a large fraction of the light misses the structure and directly affects the surrounding water. Moreover, its impact on birds must be monitored as the marshes and estuaries in this region of Spain are a stopping point for migratory birds and protected species emigrating from North Africa (Báez et al., 2007).

4.2. Novel light that halts biological colonization

Public outdoor lighting systems that illuminate important stone-built buildings in urban areas during evening hours may have biostatic effects (new and poorly known) that potentially halt biological colonization, mainly by algae and cyanobacteria. Research work in this direction has only been carried out in the past five years or so, and albeit with significant differences, is based on those carried out in hypogeal spaces such as caves and catacombs. For example, lighting systems emitting blue light in the Roman Catacombs of St. Callistus and Domitilla in Rome (Italy) have reduced by ten years the extent of cyanobacterial and chemoorganotrophic bacterial biofilms (Bruno et al., 2014; Urzì et al., 2014), and green lighting in the Nerja Cave in Malaga (Spain) has reduced growth of biofilms formed by *Chroococcidiopsis* sp., other cyanobacteria taxa, red alga, *Cyanidium* sp., and green algae (Del Rosal, 2015).

The situation in outdoor lighting is very different from that of subterranean environments, for three main reasons: (1) during the daytime solar illumination of the façade of buildings and monuments affects the development of biological colonization by phototrophs (Sanmartín et al., 2017), (2) the lighting that can be projected continuously in the urban fabric is conditioned by aesthetic aspects, as it is visible to passers-by (in caves the light is usually applied while these are closed to the public) so that it must be deemed acceptable. Blue, green and red light are not acceptable for the long-term illumination of a monument or building, and therefore the biostatic capacity must be sought in amber-white light (The CromaLux project. Available online: http://cromalux.santiagodecompostela.gal/en). Finally (3), the surrounding nocturnal biodiversity (considering the insect community as the reference group), which is specific to the open space, must be taken into account and the luminaires installed must not have any negative impact on these communities (Méndez et al., 2022). These three aspects, together with several others (e.g. the greater variability for the same area of biological colonization outside vs. inside), make achieving correct outdoor illumination with biostatic capacity against phototrophs a difficult task. Work in progress continuing research conducted within the framework of the doctoral thesis of the first author of this paper has already yielded the first good results with a prototype lamp comprising a combination of green and amber LEDs, with two peaks, one at 528 nm, and a main peak at 593 nm. However, no similar studies on lichens or bryophytes have been published. A few studies, not involving the field of cultural heritage, concerning vascular plants have been conducted, considering for example how specific wavelengths of LED lights affects the horticultural plants growth (Ma et al., 2021).

5. Final remarks, conclusions and prospects

The discrepancies as regards the definition of light pollution are reflected in existing policies and regulations, which should be up-dated to include new technologies and also reviewed and reanalysed from the point of view of sustainability. Legislators appear to find defining light pollution challenging. However, permitted concentrations of other environmental pollutants, such as particulate matter and sulphur dioxide (SO_2), have been established in regulations, facilitating control of emissions. Bará et al. (2022) suggest that light pollution levels could be expressed in terms of volume concentration of anthropogenic photons (as photons m^{-3}) in the atmosphere, so that light pollution would be considered the result of the propagation of these photons through the atmosphere. These authors also note that the establishment of artificial light levels during night in photons would help to specify exposure limits in terms of allowed atmospheric concentrations of anthropogenic light particles, unifying these with existing regulations for other atmospheric pollutants. In the case of ornamental illumination, this approach would be helpful for regulating the contribution of monument lighting to urban light pollution, which could be defined as the volume concentration of photons that outline the object shape and affect the surrounding area.

Spain has fairly detailed legislation regarding monumental illumination dispersed throughout energetic efficiency legislation and more regional environmental policies that include light pollution, in one way or another, and therefore this country can be used as an example to analyse the sustainability of the current model of ornamental illumination. Nevertheless, in most European countries the current scientific debate on light pollution is not reflected in the prevailing regulations or the as yet unavailable European light pollution common framework (Widmer et al., 2022). Light pollution is mentioned in environmental directives on different subjects such as the Biodiversity Strategy, Birds and Habitats Directives and Pollinators Initiative (European Commission (EC), 2018). However, the spotlight is only placed directly on light pollution in non-binding recommendations such as the EU Green Public Procurement (Donatello et al., 2019), which promotes ways of reducing light pollution and its negative impacts on biodiversity. From a research perspective, only a small fraction of all research on light pollution carried out between 2020 and 2022 focuses on policies developed for light pollution, and most of the body of research involves the environmental impacts of light pollution without considering the impact of its regulation. This reflects the need for a transdisciplinary approach to light pollution research in the development of regulations and policies, including lighting professionals and policymakers (Pérez Vega et al., 2021), as well as professionals involved in architecture conservation, in both science and art. With proper regulation, it would be possible to maintain an appropriate aesthetic standard, emphasising the historical and aesthetic importance of monuments, while ensuring a sustainable lighting model. This model could be achieved with technologies such as LED lighting, which has low energy consumption (Phannil et al., 2018), thus reducing emissions of CO_2 to the atmosphere (Hong and Rahmat, 2022).

In conclusion, a good balance must be struck between energy, the environment and the enhancement and conservation of stone monuments. Legislation establishes lower thresholds than health and environmental studies. However, improvements in LED technology should shift the trend towards ornamental lamps with a colour temperature between 2500 K and 3000 K and including only bands in the 500 nm to 650 nm range of the light spectrum.

CRediT authorship contribution statement

Conceptualization, P.S.; investigation, A.M., B.P., J.M.A.F., and P.S.; writing—original draft preparation, A.M., B.P., J.M.A.F., and P.S.; writing—review and editing, A.M., B.P., J.M.A.F., and P.S.; supervision, P.S.; project administration, P.S. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Data accessibility

This work has no electronic supplementary material data.

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