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Review

Light Pollution Control: Comparative Analysis of Regulations Across Civil and Common Law Jurisdictions

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Abstract: Light pollution has become an increasingly knotty environmental management problem, but little has been done to review and compare light pollution controls across the world. To address this research gap, a comparative review study has been undertaken. Among the light pollution laws of the most light-polluted regions, those pertaining to Shanghai, New York, Hong Kong, Seoul, London and Valletta were examined. We systematically evaluate the impact of legal systems, regulatory approaches and control parameters on light pollution regulation. The findings reveal that civil law jurisdictions, such as Shanghai and Seoul, typically adopt dedicated legislation while common law jurisdictions, like New York and London, often rely on bolt-on regulations to broader environmental laws. The study also finds that jurisdictions employing dedicated legislation and a metrics-based system offer a more comprehensive and preemptive solution to light pollution challenges. However, certain exceptions are noted, and the balance between regulatory certainty and flexibility is highlighted. The nuanced relationship between environmental protection and legal instruments is discussed, and the potential for unintended consequences of stringent regulation is acknowledged. The paper closes with a call for ongoing research and iterative regulatory reviews, emphasizing the need to incorporate scientific advancements and stakeholder interests into regulatory updates.

Keywords: light pollution; environmental management; regulatory frameworks; comparative analysis; legislation

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1. Introduction

Light pollution, a growing concern in the contemporary urban setting, refers to the inappropriate or excessive utilization of artificial light at night (ALAN). This phenomenon manifests in diverse forms, including heightened night sky brightness (skyglow), satellite remote sensing of upward-directed radiance from Earth's surface, ecological light pollution, surface illumination resulting from individual light sources (e.g., over-illumination of buildings), and emission spectra of individual light fixtures (Kocifaj et al. 2023).

Different forms of light pollution affect more than 80% of the world's population, rendering over 30% of it unable to view the galaxy due to the impact of light pollution on urban areas such as Hong Kong, London, and Paris (Falchi et al. 2016). The growth of the world's artificially lit outdoor area increased by 2.2% annually from 2012 to 2016 (Kyba et al. 2017). The severity of this problem is further illustrated by the significant increase in global satellite-observable light emissions, which grew by at least 49% between 1992 and 2017 (Sánchez de Miguel et al. 2021). The widespread adoption of LED technology may be masking an even larger increase in radiance within the visible spectrum, with estimates ranging up to 270% globally and 400% in specific regions (Sánchez de Miguel et al. 2021). This is exemplified by studies conducted in Madrid and Washington, which have observed shifts in sky brightness and coloration due to LED retrofits (Robles et al. 2021; Hung et al. 2021). Additionally, light pollution has increasingly encroached upon natural environments,

with the proportion of light-polluted mangrove forests in China rising from 12% in 1992 to 52% in 2020, primarily due to coastal urbanization (Zeng et al. 2023).

The harmful effects of artificial light on human health, particularly at night, are becoming increasingly evident in medical research (Lunn et al. 2017). A notable area of concern is the disruption of human circadian rhythms due to ALAN. To assess the impact of light pollution, researchers consider three main variables: light intensity, wavelength, and exposure duration. Interestingly, studies have shown that even low illuminance (1.5 lux), much lower than the typical bedroom lighting used for reading, can inhibit nocturnal melatonin production and disrupt circadian rhythms (Wright et al. 2001; Gooley et al. 2011). ALAN's ability to inhibit melatonin production has been linked to a range of health issues, including delayed sleep patterns, obesity, and insomnia in adults aged 39–70 years (Koo et al. 2016). Moreover, researchers have investigated the potential links between ALAN exposure and breast cancer risk (James et al. 2017; Lai et al. 2021). Large cohort studies have also examined the relationship between residential outdoor LAN exposure and overall breast cancer, as well as the potential connection between LAN and estrogen receptor-positive breast cancer (Clarke et al. 2021). A nationwide cohort study utilizing Austrian birth registry data discovered that higher light pollution levels correlate with increased odds of prolonged labor, adverse neonatal outcomes, and preterm delivery. On the other hand, addressing light pollution as a modifiable risk factor could help minimize associated health risks and adverse outcomes in obstetrics (Windsperger et al. 2022).

Blue light pollution warrants particular concern because of its potential to cause retinal damage and degeneration by inducing ferroptosis, a cell death pathway involving excessive lipid peroxidation (Li et al. 2023). Blue-rich light from LEDs serves as an endocrine disruptor, necessitating further investigation to comprehend its risks and determine suitable exposure limits for vulnerable populations (Touitou and Point 2020). A Swiss study found that a 2 h exposure to monochromatic light at 460 nm in the late evening significantly suppressed melatonin production, whereas the same intensity and exposure time at 550 nm did not yield such effects (Cajochen et al. 2005). These findings suggest that wavelength may be as effective a parameter as light intensity for evaluating the impact of light on humans and measuring light pollution. Beyond its impact on human health, light pollution has also been shown to affect the behavior and physiology of marine invertebrates, as demonstrated by a study on European hermit crabs (Mander et al. 2023). Exposure to constant light reduces boldness and increases metabolic rates in European hermit crabs, potentially affecting their risk coping mechanisms and energy balance. Another study highlights the negative effects of light pollution on marine invertebrates' behavior and physiology (Mander et al. 2023). However, reduction of blue light in amber LED streetlights was found to be ineffective at improving sleep in urban black swans when compared with blue-rich white LED streetlights, suggesting that blue light reduction might not be universally effective for mitigating the effects of artificial light on sleep in all species (Aulsebrook et al. 2020).

Research has shown strong correlations between light pollution, population density, and GDP, highlighting the prevalence of this issue in densely populated metropolises (Aksaker et al. 2020). In Hong Kong, for example, night sky brightness levels are exceptionally high, far exceeding the standards set by the International Astronomical Union (IAU) (Pun et al. 2014). A study conducted in Korea has further revealed that mixed land-use areas, which combine residential and commercial activities, are at greater risk of light pollution (Cheon and Kim 2020). Some photos presenting Hong Kong's severe light pollutions are shown in Figure 1a–c.

Compared with other forms of pollution, light pollution is apparently more manageable. For instance, during the coronavirus pandemic in Cracow, Poland and neighboring municipalities, the temporary switch-off of street lighting led to a significant decrease in radiance. Light energy radiated into the sky reduced by approximately 50% in urban areas, and the surface brightness of the night sky declined by about 40%. This effect was found to

be most pronounced in highly urbanized urban or urban–rural communes, highlighting the considerable contribution of street lighting to light pollution (Ściężor 2021).

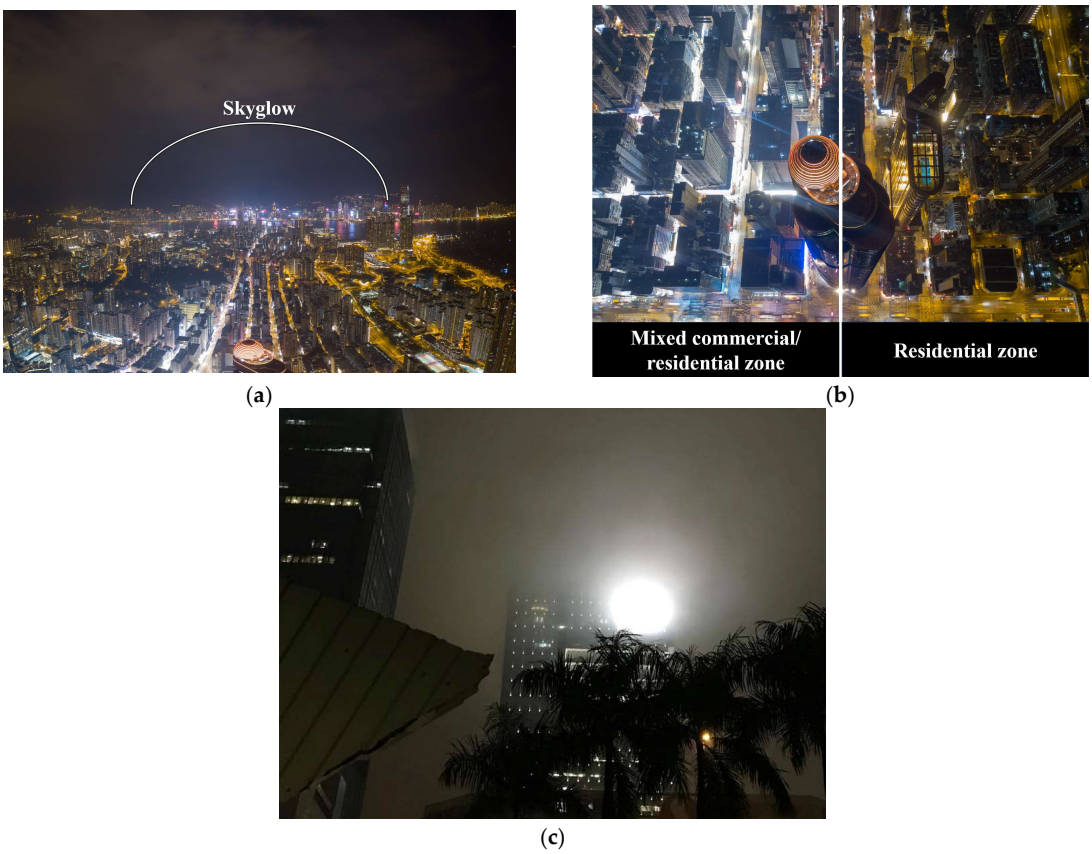

Figure 1. (**a**) Skyglow, (**b**) over-illumination of buildings in mixed commercial/residential zone, and (**c**) glare caused by excessive light in fog.

In the realm of pollution control, there are two distinct regulatory approaches, namely, hard law and soft law (Druzin 2017; Kassie 2024). Hard law refers to legally binding and enforceable rules, statutes, regulations and treaties that have the force of law and are typically accompanied by specific mechanisms for enforcement and sanctions in the event of non-compliance. Hard law can be further divided into dedicated legislation and bolt-on approaches to existing legislation (Morgan-Taylor and Kim 2016). On the other hand, soft law comprises non-binding instruments, guidelines, principles, declarations and codes of conduct, serving as a tool for shaping behavior, fostering cooperation and guiding decision making in a more flexible and voluntary manner (Coglianese 2020; Zhu and Tang 2024). While voluntary compliance could be a way to reduce light pollution, mandatory requirements akin to those imposed on other aspects of environmental pollution (e.g., air, water, solid waste) are often inevitable for controlling light pollution activities. Yet, what are these light pollution regulatory controls across different regions in the world? Are there commonalities or differences between these controls? What observations can be obtained by comparing these controls? Built upon such observations, what actions or studies can be undertaken for improving the global control on light pollution? As previous research seeking to answering these questions is limited, the work of a preliminary study (Law and Lai 2019; Morgan-Taylor and Kim 2016; Morgan-Taylor 2023) was substantially extended so as to complete the present research study.

2. Methods

The methodology of this study comprises three steps: identifying the most light-polluted regions, searching relevant statutory light pollution requirements of the identified

regions, and reviewing those requirements in depth. In identifying the most light-polluted regions, we referred to the World Atlas of Artificial Sky Brightness, which was prepared using advanced light pollution propagation software, high-resolution satellite data, and precise sky brightness measurements (Falchi et al. 2016). The identified regions are as follows: North America's Boston to Washington corridor; European countries including the Netherlands, San Marino, Malta, Belgium, Germany (specifically, the Dortmund to Bonn cities), England (from London to the Liverpool/Leeds region) and France (Paris area); the Asian region including Singapore, South Korea, and regions surrounding Beijing and Hong Kong in China; the Middle East, comprising Kuwait, Qatar, United Arab Emirates, Saudi Arabia, and Israel; Argentina in South America; Libya in Africa; and Trinidad and Tobago in the Caribbean. Given the language barriers posed by non-English-speaking regions, documents covered by this review study are confined to areas where English is the official or primary language. As a result, several European countries (with the exception of England and Malta), Middle Eastern regions, Argentina, Libya, and South Korea are excluded from our analysis. As English publications about the light pollution laws of Seoul, South Korea were identified during the literature search process (Ngarambe and Kim 2018), such statutory requirements are also included in the present review study.

In the second step, extensive searches were carried out to retrieve the existing light pollution laws of the regions identified above. The legal research databases used for this purpose include LexisChina, Lexis Advance Hong Kong, Lexis Advance Hong Kong Research, Law 360 and Westlaw Asia. To locate the most updated and the most relevant search results from these databases, jurisdictional filters (including China, Hong Kong, India, Malaysia, Singapore, the United Kingdom (UK), Australia, New Zealand, Canada, and the United States of America) and keywords (including 'light pollution' and 'law' or 'legislation' or 'statute') were adopted. Our findings reveal that New York, Malta, Shanghai, Hong Kong, the UK, and Seoul have implemented light pollution laws.

Lastly, an integrative review approach was taken to combine relevant perspectives for generating new insights (Snyder 2019). Thus, manual content analysis was conducted by the research team to scrutinize the provisions of the laws of the identified regions, appraise their requirements, and compare their characteristics. Through discussing the review findings, implications are identified, signposting the future directions for improving light pollution control.

3. Findings

3.1. Existing Regulation Regime on Light Pollution

The light pollution regulations of Shanghai, Hong Kong, Seoul, New York, London and Valletta (see Table 1) were selected for analysis for three reasons. First, these jurisdictions represent diverse geographical regions and cultural backgrounds. Second, they have different light pollution levels and focus of regulatory frameworks. Third, they have different economic profiles and levels of development, which impact their ability to implement and enforce regulations effectively. By scrutinizing the provisions of the light pollution laws of these cities, an understanding of the focus of their regulatory approaches can be obtained, which will yield insights on the implementation of legislative controls on light pollution.

Table 1. The six cities studied.

	Shanghai (China)	**Hong Kong (China)**	**Seoul (South Korea)**	**New York (United States)**	**London (United Kingdom)**	**Valletta (Malta)**
Area (km^2)	6300	1100	600	780	1570	0.8
Population (million)	24.8	7.5	9.5	8.4	8.8	0.006
Continent	Asia	Asia	Asia	America	Europe	Europe

Note: Countries in parentheses.

3.1.1. Shanghai

Instead of a national legislation dedicated to controlling light pollution, there are national laws in China imposing governance on matters that may relate to light pollution, e.g., Article 83 of the General Principles of the Civil Law, Article 90 of the Property Law, and Article 42 of the Environmental Protection Law. In these laws, "Lighting" can be classified as a harmful substance or source of damage. Moreover, Article 65 of the Tort Liability Law mandates that polluters bear tort liability for damage resulting from their environmentally polluting actions.

In the landmark case Li Jin v. China Resources Land (Chongqing) Co., Ltd., Chongqing, China (Guiding Case No. 128 of the 24th Batch of Guiding Cases Issued by the Supreme People's Court), the court identified three elements constituting tort liability: (i) the polluter's environment-polluting act, (ii) the plaintiff's demonstrable damages, and (iii) a causal relationship between the plaintiff's damages and the defendant's actions. Although light pollution may not cause clearly identifiable health issues or quantifiable damages, the court underscored the significance of safeguarding plaintiffs' environmental rights and interests. Throughout the four-year legal process, the court consulted urban planning and lighting technology experts to evaluate the health impacts of intense light exposure. The final ruling mandated the tortfeasor to limit LED luminance (within 600 cd/m^2) after 19:00 and adhere to a specific operating schedule (turn on after 08:30, off before 21:50/22:00).

In 2017, the Standardization Administration introduced the "specification for limitation to obtrusive light of outdoor lighting", which incorporated concepts such as "lighting zones", "curfew", "maximum illuminance exposed to windows of residential buildings", "maximum luminance of different light source facilities", and "upward light output ratio". In 2018, the national standard "GB/T 36101-2018—Evaluation requirements for obtrusive light of LED panels" was issued, outlining the lighting requirements for LED panels (General Administration of Quality Supervision, Inspection and Quarantine and Standardization Administration of the People's Republic of China 2018). Under the Standardization Law, local governments have the authority to investigate and penalize suspected non-compliance.

Since 2022, the Shanghai Municipality of Environmental Protection has amended the Regulations of the Shanghai Municipality on Environmental Protection to control light pollution. Articles 64 to 66 focus on strengthening source control for various lighting types, including road, landscape, outdoor advertising, billboards, and building exteriors, ensuring they meet relevant technical standards. The authorities also have the power to regulate lighting duration and on/off times for light shows in central business districts. According to Article 93, individuals who violate Article 66 may face fines ranging from 10,000 to 50,000 yuan. Those who install non-compliant lighting and neglect to remove it upon request may be subject to fines between CNY 5000 and 50,000.

3.1.2. Hong Kong

Besides a broad range of regulations governing building services construction and maintenance (Lai and Yik 2004; Lai et al. 2011), Hong Kong has implemented soft law to control light pollution resulting from road lighting and building usage. The Highways Department's "Public Lighting Design Manual" prescribes upward light ratio limits and window light intrusion restrictions for road lights. Rather than considering the broader nighttime environment, the manual focuses on reducing contrast between objects and their background to maintain driver visibility at night.

A voluntary accreditation scheme, "BEAM Plus", addresses the sustainable design in both new and existing buildings. In BEAM Plus New Buildings Version 2.0, credits are awarded for adequate light pollution mitigation measures during construction and sustainable site management. To earn credits, applicants must comply with the guidelines from The Institution of Lighting Professionals and the Model Lighting Ordinance (MLO), which, rather than being an established ordinance in Hong Kong, is a framework developed by the International Dark-Sky Association and the Illuminating Engineering Society (2011) to assist municipalities in establishing outdoor lighting standards aimed at reducing glare,

light trespass, and sky glow. They must also demonstrate that external surfaces such as glass meet the maximum light reflectance thresholds. They must also submit a backlight–uplight–glare (BUG) report, demonstrating that the luminaire uplight, backlight and glare ratings for the specific light source do not exceed the criteria for the defined lighting zone as outlined in the MLO. In accordance with green government buildings (Development Bureau Technical Circular No. 2/2015 and Environment Bureau Circular Memorandum No. 3/2015), new government buildings are generally required to obtain a minimum second-highest grade accredited under BEAM Plus.

Another scheme, BEAM Plus Existing Buildings (both selective and comprehensive schemes), covers the minimization of light pollution from external lighting. Full credits are awarded if no external lighting fixtures are installed or if they are switched off between 23:00 and 07:00. Since 2016, the voluntary "Charter on External Lighting" scheme has required participating buildings to turn off external lights from 22:00 to 07:00, and, with stricter requirements introduced in 2023, the switch-off time has been changed from 23:00 to 22:00.

3.1.3. Seoul

Article 2 of the national law "Act on The Prevention of Light Pollution due to Artificial Lighting" defines the causes of light pollution and highlights the lighting fixtures used for illumination, advertisements and decorations (Cha et al. 2014). Article 3 of the act stipulates that local governments should consider regional characteristics when formulating and implementing measures to prevent light pollution. Article 11 empowers special metropolitan cities to establish stricter standards for light emission than the national standard. Chapter 5 of the act specifies administrative fines (KRW 1 million to 10 million) for failing to comply with correction orders, failing to observe the defined standard of light emission, rejecting inspection, and so forth. In particular, Article 9 introduces the concept of "Lighting Environment Management Areas". "Class 1 district" refers to zones where the natural environment is more susceptible to excessive artificial lighting; "Class 2 district" refers to zones where agriculture, forestry, fisheries, and the growth of animals and plants are more susceptible to excessive artificial lighting; "Class 3 district" refers to zones where the residential life of people is more susceptible to artificial lighting; "Class 4 district" refers to zones where commercial activities are in place, but excessive artificial lighting may cause an unpleasant and unhealthy lifestyle for people.

In 2010, the Seoul metropolitan government enacted an ordinance on the prevention and management of light pollution (Guanglei et al. 2019). The legislation has multi-layered regulations to prevent light pollution. First, it carefully defines the light source facilities to be regulated, namely, "space lighting", "advertising lighting", and "decorative lighting". Second, it divides the city into four classes of lighting environment management districts—as mentioned above. Third, the legislation applies metric systems mixed with curfews to manage different lighting zones. The authority not only prescribes permissible luminance values for defined light source facilities in zones but also standardizes the maximum permissible luminance on windows (the receivers). During curfews, decorative lighting must be turned off no later than 23:00. Since the implementation of Seoul's light pollution laws in 2010, complaints significantly declined from 1558 to 706 in 2011. Nevertheless, a marked increase began in 2014, culminating at 1571 and indicating possible heightened issues or public awareness. Continued monitoring and regulation are necessitated by these trends (Park et al. 2017). In 2019, the authority amended the law to delegate light pollution management agencies to inspect whether streetlights and advertising lights comply with the lighting standards.

3.1.4. New York

New York City has adopted a "bolt-on approach" to regulate light pollution caused by public buildings. In 2014, Senate Bill 2013-S5275B established design specifications for any new lighting fixtures purchased by the state, with the aim of limiting misdirected and

excessive outdoor illumination. This bill was subsequently incorporated into N.Y. Public Buildings Law §143, which prohibits the use of state funds for installing new permanent outdoor lighting fixtures or covering the cost of operating such fixtures unless specific requirements are met. These requirements mandate the use of fully shielded fixtures, with exceptions for building-mounted fixtures emitting an initial lumen output of less than 3000 and ornamental roadway lighting fixtures with a lowest light-emitting part producing less than 700 lumens above a horizontal plane.

In 2022, the New York City Council enacted local laws (File No. Int 0274-2018) amending the local administrative code concerning nighttime illumination during peak avian migration periods. This "bolt-on" legislation requires all non-essential state-owned and managed buildings to turn off non-essential outdoor lighting between 23:00 and 06:00 during peak bird migration periods, which occur from 15 April to 31 May and from 15 August to 15 November. During these periods, all outdoor lighting that does not serve safety or functional purposes must be switched off.

3.1.5. London

In London, a bolt-on approach is employed, which incorporates specific clauses of lighting nuisance into hard law rather than creating dedicated legislation. Initially, the Environmental Protection Act 1990 (EPA 1990) did not include provisions that specifically address light pollution. However, section 102 of the Clean Neighbourhoods and Environment Act 2005 amends section 79 of the EPA 1990 to include nuisance from artificial light. Section 102(2) of the Clean Neighbourhoods and Environment Act 2005 establishes a distinct form of artificial light nuisance, defined as "artificial light emitted from premises so as to be prejudicial to health or a nuisance", and classifies it as a criminal offense. However, this law does not explicitly address the form or level of light pollution; instead, it focuses on incidents involving inappropriate lighting from certain types of premises that cause nuisance. The EPA 1990 serves as the primary legislation for addressing various environmental nuisances, including light pollution.

In Birmingham City Council v Oakley [2001] 1 AC 617, the House of Lords clarified the term "prejudicial to health" used in section 79(7) of the EPA 1990 to mean "injurious, or likely to cause injury, to health". Although light pollution is a relatively new subject in the medical field when compared with hygiene, emerging research suggests that excessive light can adversely affect sleep patterns (House of Lords 2015). To establish that something is "prejudicial to health", credible scientific evidence is necessary, illustrating that excessive light constitutes harm and poses a significant risk to health, irrespective of hypersensitivity. This requirement presents an evidentiary challenge, as the level of light harmful to health is not universally agreed upon and must be evaluated on a case-by-case basis, taking into account multiple factors, including potential negative health impacts (Department for Environment, Food and Rural Affair 2015).

3.1.6. Valletta

Valletta has multiple legal and policy frameworks for addressing light pollution. Pursuant to Article 58(1) of the Environment Protection Act 2016 (Cap. 549), activities expected to generate, intensify or modify light pollution, or other disturbances to the environment are prohibited. The Subsidiary Legislation 552.28 of the Billboards and Advertisements Regulations 2017 of the Development Planning Act (Cap. 552) stipulates that illuminated advertisements and billboards will "only be permitted where they do not give rise to unacceptable levels of light pollution and do not prejudice third party rights". Moreover, this kind of external lighting should cause no light pollution (e.g., internal illumination, oriented downwards illumination, limited brightness), visual intrusion or disturbance to the surrounding environment (e.g., flickering effects). Brightness limit (max. 300 cd per m^2 during the day and 100 cd per m^2 during the night) is specified for the safety of the motoring public. The size of any billboard and advisement as well as the longitudinal distance between successive billboards that face in the same direction is regulated. In 2015,

Malta Environment and Planning Authority (MEPA) published the "Development Control Design Policy, Guidance and Standards", of which item G27 specifies the requirements for any proposed development or redevelopment, for example, full cut-off type, downward-pointing, zero intensity at and above the horizontal, etc. This document is not legally binding but serves as a useful resource for developers, architects, and designers who are seeking to minimize the impact of their lighting installations on the environment and surrounding communities.

Of note, the Subsidiary Legislation 552.08 of the Development Notification Order 2016 of the Development Planning Act (Cap. 552) stipulates that external lighting of buildings, structures and roads, if it is incompatible with the character of the location, will not be permitted. Artificial nocturnal lighting or lighting that will compromise the conservation of important flora, fauna or ecosystems are also banned. In 2020, the Environment and Resources Authority and Planning Authority launched a public consultation process for the "Guidelines for the Reduction of Light Pollution in the Maltese Islands", which mentions that any sources of light intended for exterior illumination should have a correlated color temperature not higher than 3000 K. However, the final version of this guideline has not yet been published. In October 2021, the Green Public Procurement National Action Plan 2022–2027 was published, which only allows low light pollution lighting equipment that fulfills (i) a 0.0% of ratio of upward light output, (ii) a G index of $\geq$1.5 (a G-index of $\geq$1.5 would generally (but not always) equate to a CCT of $\leq$3000 K) to be purchased during public procurement, and (iii) a ready dimming program for ecologically sensitive locations.

3.2. Legal Systems and the Focus of Regulatory Approaches

The diverse legal systems and the focus of regulatory approaches across the above jurisdictions are summarized in Table 2.

Table 2. Comparison of light pollution controls.

	Shanghai	**New York**	**Hong Kong**	**Seoul**	**London**	**Valletta**
Legal system	Civil Law	Common Law	Common Law	Civil Law	Common Law	Mixed
Focus of regulatory approach	Dedicated legislation	Bolt-on	Soft Law	Dedicated legislation	Bolt-on	Bolt-on
Relevant hard/soft law	Evaluation requirements for obtrusive light of LED panels (GB/T 36101-2018), regulations of Shanghai municipality on environmental protection	N.Y. Public Buildings Law §143	BEAM Plus, public lighting design manual Charter on external lighting	Act on The Prevention of Light Pollution due to Artificial Lighting, Seoul Light Pollution Ordinance	Clean Neighbourhoods and Environment Act 2005	Development Planning Act (Cap. 552), Environment Protection Act (Cap. 549)
Control focus	Outdoor LED panels, road lighting, landscape lighting, building's external wall reflection	Stated-funded public lighting	Public roads, government buildings, decorative and advertisement lighting	Decorative and advertisement lighting	Artificial light emitted from premises	Outdoor advertisements and billboards
Control ground	Metrics	Metrics	Metrics	Metrics	Nuisance	Metrics

Table 2. *Cont.*

	Shanghai	New York	Hong Kong	Seoul	London	Valletta
Control parameter	Brightness, size and positioning, window illuminance, repair frequency	Upward light ratio, lumen output, light schedule	Upward light ratio, light level, light schedule	Upward light ratio, light level, light schedule	Prejudicial to health	Brightness, size and positioning
Exemption	Construction works with proper light control measures	Lighting for aviation and nautical safety, athletic playing areas, tunnels, roadway underpasses, emergency procedures	Not applicable	Determined by the mayor	Airports, harbour premises, prisons, vehicle operating centre, lighthouse and transport depots	Used for moving vehicles, political, legal, feast, traffic signs, flags, limited size, inside buildings, NGO activities

Note: Detailed requirements refer to the respective laws.

Civil law jurisdictions, including Shanghai and Seoul, tend to embrace dedicated legislation tailored specifically for light pollution management. On the other hand, common law jurisdictions, like New York and London, often rely on bolt-on regulations, integrating light pollution controls within broader environmental protection laws. Hong Kong, another common law jurisdiction, uniquely adopts a softer approach by employing quasi-legal instruments, such as the voluntary charters and building certification schemes, to guide and promote best practices in light pollution management. Valletta, distinctively possessing a mixed legal system, employs a bolt-on approach within its existing environmental legislation.

It can be observed that dedicated legislation that employs a metrics-based system has the potential to address all environmental and human health problems related to light pollution. This approach is capable of limiting light operation time, light levels, and even light color, rather than being confined to one or two aspects such as nuisance or human health. This approach provides a comprehensive understanding of the problem, facilitating compliance and acting as a precautionary measure by which to control light pollution before it worsens. In contrast, London adopts a "bolt-on approach", which acts as a reactive means of control, relying on significant evidence that demonstrates the degree of light trespass affecting daily enjoyment and prejudicial light levels. While this bolt-on approach is taken from a public health perspective, the legal definition of light pollution complicates the regulatory enforcement and puts citizens in a passive position when addressing the nuisance caused by light pollution.

Valletta and New York's light pollution control exhibit a unique combination of a bolt-on approach and metrics. However, the level of control is limited, as the scope and coverage of the control are constrained by pre-existing laws. Sole restriction on the light quality of public lighting is insufficient to mitigate the light pollution issue. Additionally, public lighting remains on at night primarily due to safety and security perceptions. However, research (Steinbach et al. 2015; Marchant and Norman 2023; Marchant et al. 2020) indicates a weak correlation between ALAN and actual safety outcomes, challenging the assumption that increased lighting enhances security. This suggests that municipalities may maintain excessive lighting without clear evidence of benefit, warranting the reevaluation of such practices in light of health and environmental concerns.

Dedicated legislation with a metrics system presents a benefit of certainty in light pollution control, while the bolt-on approach generally offers flexibility. The question is whether the benefit of certainty outweighs the benefit of flexibility. Valletta serves as an exemplary case for striking a fair balance among different factors. Planning controls could

act as proactive measures by which to reduce the regulatory burden of inspectorate staff during enforcement of the law. However, control is predominantly focused on signboards, which may be subject to changes as per local needs.

The scope of regulation varies across the jurisdictions, with some emphasizing outdoor LED panels, road lighting, and landscape lighting (Shanghai), while some others focus on public roads, government buildings (New York and Hong Kong), or decorative and advertisement lighting (Seoul). Overall, most of the jurisdictions studied cover the control of advisement and relevant lighting. However, some lighting is exempt from regulatory control, e.g., lighting for security and public use reasons to cater for different needs for safety, security and economy (Morgan-Taylor 2015).

3.3. Control Parameters

While the UK employs a nuisance-based approach, regulating artificial light emissions that are prejudicial to health, the relevant hard and soft laws of the other jurisdictions in Table 2 show the adoption of metrics-based control grounds, where specific engineering parameters, such as vertical illuminance, brightness, light intensity, upward light ratio, curfew, color temperature and repair frequency, are used (See Table 3). Among these jurisdictions, Shanghai, Seoul and Valletta have adopted specific engineering metrics, such as brightness limitations, to curb light trespass. Additionally, Shanghai and Seoul regulate vertical illuminance on window surfaces to further mitigate light trespass.

Table 3. Comparison of light pollution regulation metrics.

	Shanghai	**New York**	**Hong Kong**	**Seoul**	**Valletta**
Vertical illuminance (window surface)	✓	-	-	✓	
Brightness	✓	-	-	✓	✓
Light intensity	✓	-	-	-	-
Upward light ratio	✓	✓	-	-	-
Curfew	-	✓ 23:00–06:00	✓ 22:00–07:00	-	-
Color temperature	-	-	-	-	≤3000 K
Repair frequency	Monthly	-	-	-	-

Note: "✓" means the metrics-based control has been in place; "-" means there is no such control; Detailed requirements refer to the respective laws.

Both Shanghai and New York have implemented controls on upward light ratios to reduce skyglow. However, in New York, these restrictions apply primarily to government buildings and certain types of lighting, potentially limiting their overall effectiveness.

New York and Hong Kong enforce curfew hours to restrict the use of artificial lighting during specified nighttime periods. This strategy offers a direct and straightforward approach to minimizing light pollution during critical hours when human health and the natural environment are most vulnerable. However, the curfew in New York is mandated only during bird migration periods, while Hong Kong relies on voluntary compliance, which may affect the consistency and efficacy of the policy.

China's light pollution control standards exhibit extensive coverage across various aspects of light pollution management. The diverse approaches taken by different jurisdictions highlight the importance of developing context-specific strategies that address local challenges and priorities. Nevertheless, it is crucial to ascertain whether full adherence to the metrics outlined in Table 3 would absolve operators of potential liability for their light emissions. While the establishment of regulatory metrics is straightforward and provides a robust framework, it remains inexplicit whether these metrics serve as a discrete bar to liability or sufficient evidence that operators or owners have exercised all reasonable steps and due diligence to prevent adverse impacts on others.

3.4. Control Limit Values

The values of maximum allowable vertical illuminance on residential windows in Shanghai and Seoul, categorized by distinct environmental zones (E1 to E4/E4*) and specific time periods, are compared in Figure 2, with a notable similarity in the definition of environmental zones between the two cities (Guanglei et al. 2019). These illuminance limits are determined by the respective light management zone and feature heightened restrictions during curfew hours. In particular, Seoul applies a consistent limit across zones E1, E2, and E3, spanning the period from 60 min after sunset to 60 min before sunrise.

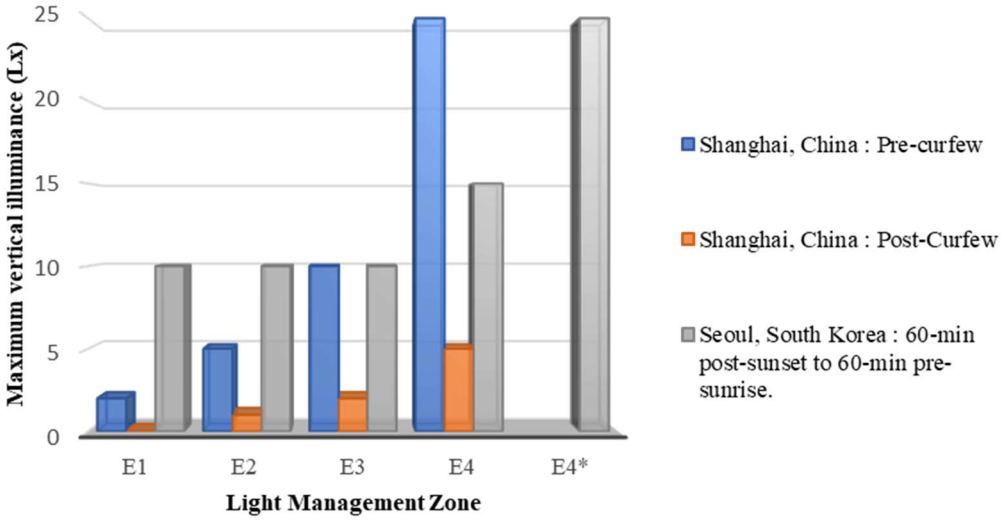

Figure 2. Maximum vertical illuminance on residential windows in Shanghai and Seoul (Note 1: Seoul divides the E4 zone into semi-industrial (E4) and industrial and commercial zones (E4*); Note 2: In proximity to public (road) lighting, Shanghai permits a rise to 1 lx in Zone E1's illuminance).

Shanghai's approach to light management is notably stringent. The city enforces a zero-lux limit on residential windows in zone E1 and a maximum of 5 lux in zone E4. Intriguingly, this limit in zone E4 is a mere 20% of the equivalent pre-curfew limit in both Shanghai and Seoul's corresponding zone (E4*). When comparing zones E2 and E3, Shanghai's limits are more restrictive than those in Seoul. Specifically, in zone E2, the pre-curfew limit in Shanghai is half of that in Seoul, whereas the post-curfew limit is only one-tenth. In zone E3, the pre-curfew limit is identical to Seoul's, but the post-curfew limit in Shanghai is reduced to 20% of Seoul's limit.

In addition to regulating vertical illuminance on residential windows, Shanghai adopts a "two-sided" approach to control the light intensity of luminaires directed at residential windows (see Figure 3). This limit applies across environmental zones (E1 to E4) and is stratified into time periods before and after the curfew. Mirroring the restrictions on vertical illuminance, Shanghai imposes stricter light intensity constraints during curfew hours, aiming to mitigate the impact of light pollution on its residents during the night. While the national standard permits 10 cd in Zone E1 after the curfew, Shanghai authorities enforce a policy of zero light intensity, demonstrating the city's commitment to minimizing nighttime light pollution.

The approaches of Valletta, Shanghai and Seoul to controlling light pollution caused by advertisement lighting vary significantly, as evidenced by the distinct metrics adopted (see Figure 4). Contrasting Valletta's generalized approach, Shanghai and Seoul have developed comprehensive frameworks that address a broad spectrum of lighting categories, inclusive of advertisement lighting and other commercial applications. As regards the regulations on advertisement lighting, Shanghai and Seoul have comparable restrictions for advertisements or outdoor signboards across all zones.

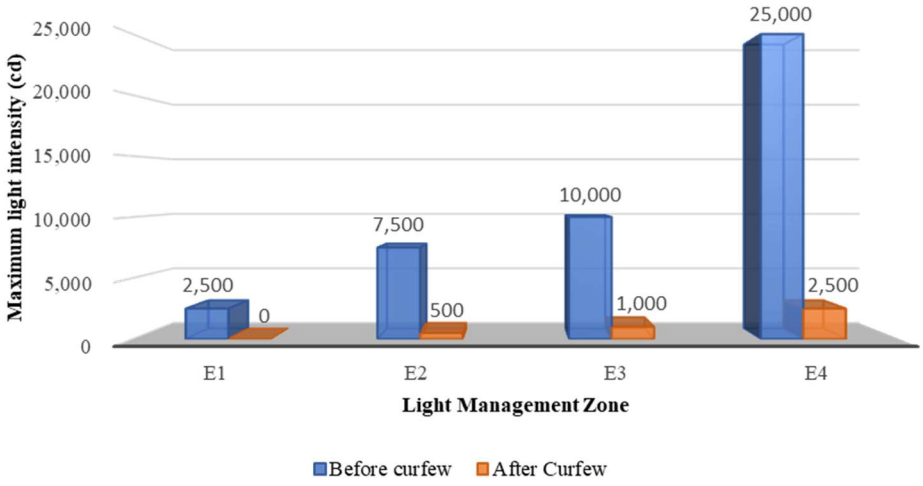

Figure 3. Permissible light intensity for luminaires directed at residential windows in Shanghai (Note: In Zone E1, the light intensity limit may rise to 500 cd when near public (road) lighting).

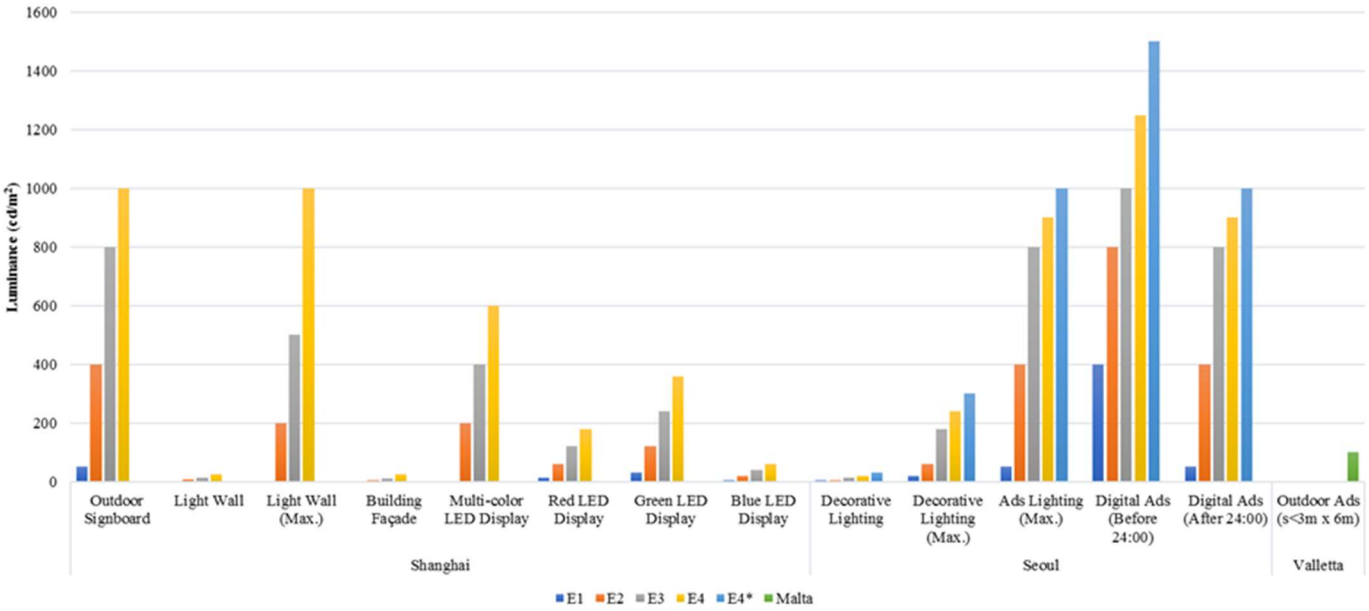

Figure 4. Luminance limits for various lighting categories in Shanghai, Seoul and Valletta (Note 1: Unless specified, luminance refers to average limits. Note 2: Shanghai's outdoor signboard rules apply at night (18:00–06:00, 19:00–05:00 in summer). For LED displays, limits refer to a full white screen. Nighttime limits for dynamic signs are halved. Note 3: Shanghai's light wall limits can rise by 50% for key landscape or façade enhancements yet drop by 50% for dynamic effects. Note 4: Shanghai mandates a 50% limit reduction for dynamic multi-color displays in ads and banners).

Of all the jurisdictions evaluated, Seoul stands out as the only one to impose limits on decorative lighting, with the stipulated maximum average brightness being 15–40% of that allowed for advertisement lighting. Shanghai also distinguishes itself by being the only jurisdiction to regulate light walls and building façade and to control LED displays by their color, including multi-color, blue, green, and red. Blue-colored displays are imposed with the most stringent control, being a mere 17% of that for green-colored LED displays.

Shanghai's restrictions on luminance are notably more stringent compared with the other jurisdictions. For instance, light walls and multi-color LED displays are prohibited in Shanghai's E1 zone. In contrast, Seoul permits digital advertisements with a brightness of 400 cd/m^2 before 24:00 and 50 cd/m^2 after 24:00 in the same zone. Generally, Shanghai's control of multi-color LED displays is more stringent that of Seoul. It is noteworthy

that the brightness limit for multi-color LED displays in Shanghai's E4 zone is set at 600 cd/m^2, which is 48% and 67% of the limits in Seoul before and after 24:00 respectively. Comparatively, Seoul's limits (after 24:00) in zone E4* are still 1.6 times higher than those of Shanghai's E4 zone. Given that typical television displays utilized in residential settings exhibit luminance levels of approximately 400 cd/m^2 for a white screen and between 100–200 cd/m^2 for average displayed content, the luminance limits prescribed in both Shanghai and Seoul appear disproportionately high. This observation necessitates a critical evaluation of the current regulatory framework, as such elevated limits may not sufficiently account for the potential negative ramifications on urban environments and public health.

Just as Valletta regulates color temperature, Shanghai imposes controls on LED displays, including brightness levels under red, green, and blue lights. The restrictions on blue light are particularly stringent, followed by red and green. In Shanghai's E4 zone, blue LED displays are allowed provided their brightness does not exceed 60 cd/m^2, a limit similar to that of general advertisements and banners in the E1 zone.

4. Discussion

4.1. Impact of Legal System on Light Pollution Regulation

The above analyses reveal that the legal system of a region greatly influences its light pollution regulation. Civil law jurisdictions such as those of Shanghai and Seoul typically adopt dedicated legislation to manage light pollution. Conversely, jurisdictions with a common law system, including Hong Kong, New York and London, often employ a bolt-on approach, relying on the existing nuisance law provisions. Interestingly, this taxonomy is also observed in civil law jurisdictions such as those of Spain and France (Ministry of the Environment of the Czech Republic 2022) although they were not within the scope of the present study. The question of which factors might have contributed to this observation should warrant further study.

Civil law systems, prevalent in countries including South Korea and China, consolidate fundamental principles into a codified system that serves as the primary law source (Zweigert and Kötz 1998). This structure tends to foster comprehensive legislation addressing various aspects of a particular subject, including environmental law and light pollution. In contrast, common law systems, such as those adopted in Hong Kong, the United States and the United Kingdom, are precedent-based, with the laws developed from court decisions and tribunals (Zweigert and Kötz 1998). These jurisdictions often apply existing legal norms to new situations, including environmental issues, through the bolt-on approach. In terms of light pollution, these jurisdictions may not have specific legislation but rather control it through broader provisions, like nuisance law (Bell et al. 2007).

Nevertheless, it is important to recognize the notable variations within both civil and common law jurisdictions. Environmental regulation approaches are also influenced by a multitude of factors, such as political determination, public sentiment, and the influence of environmental advocacy groups. Furthermore, the demarcation between the two systems can be less clear-cut, with common law jurisdictions sometimes enacting broad legislation to address emerging issues and civil law jurisdictions occasionally depending on court interpretation to apply legislative provisions to particular circumstances.

4.2. Dedicated Legislation vs. the Bolt-On Approach

Dedicated legislation often leans towards command-and-control strategies, but these can lead to unforeseen consequences, or "rebound effects". For instance, the US Endangered Species Act has protected many species but has inadvertently incentivized landowners to deter protected species to avoid land-use restrictions, an effect known as "shoot, shovel, and shut up" (Lueck and Michael 2003).

The bolt-on nuisance regime has its advantages, as enforcers can evaluate the overall impact of lighting using broader concepts than a fixed set of metrics. This flexibility raises the question of whether the certainty's benefit outweighs the disadvantage of its inflexibility. Regularly reviewed and updated metrics offer a promising regulatory opportunity.

Critics argue that voluntary measures are too lenient, but they have been effective in areas such as renewable energy. For instance, Green-e Energy, a voluntary certification program in the United States for renewable energy, has boosted consumer confidence and demand. However, its success hinges on voluntary participation from energy companies and consumers (Bird et al. 2007). For example, the voluntary approaches in Hong Kong on light pollution have been met with limited success. The number of complaints related to external lighting has increased by 45% over five years, raising concerns about the effectiveness of voluntary approaches (Environmental Protection Department 2020). In the design and implementation of voluntary measures, it is crucial to consider diversified strategies, establish diffusion networks, and bridge the gap between early adopters and the majority (van der Heijden 2020). While focusing on the participation of a smaller subset of society may yield positive results, it is equally important to address the needs and engage the remaining participants, including those working or residing in highly dense and crowded zones. Notably, soft law can sometimes serve as a precursor to hard law, potentially leading to earlier impacts on pollution reduction than hard law itself (Zhu and Tang 2024; Skjærseth et al. 2006)

4.3. Unintended Consequences of Dedicated Legislation in Environmental Protection

Given the complexity of socio-economic systems, regulations and policies can inadvertently lead to undesirable outcomes. Command-and-control regulations can effectively realize specific outcomes, yet they might lack flexibility and impose substantial compliance costs (Hahn 2000). For example, the city of New York has imposed constraints on construction noise, affecting the industry. These requirements can be costly, necessitating investments in noise mitigation strategies, potentially prolonging projects and escalating costs (New York Building Congress and New York Building Foundation 2008). Some firms, especially those with narrow profit margins or existing financial difficulties, might find these costs unbearable, leading to non-compliance as a cost-saving strategy.

Based on the above example, we can foresee that the rebound effect may include overuse in non-regulated times and areas for overcompensation for restrictions during curfew hours, redirecting lights away from regulated areas, or increasing light clutter by adding more fixtures with lower individual output but more complex arrangements. Such effects can worsen pollution problems, endanger public health, harm local ecosystems, and necessitate increased government expenditure on cleanup and enforcement activities.

4.4. Future Directions

In environmental legislation, the crux lies not solely in the decision to regulate but also in the method of regulation. Applicable tools range from command-and-control regulations to market-based approaches and voluntary strategies, all underpinned by various environmental principles (Goulder and Parry 2008; Rutherford 2022). Regulation inevitably entails various costs, including those for administration, enforcement, inspection, monitoring, and evaluation. The rebound effects, including financial burdens on businesses and individuals, must be carefully balanced against potential societal and environmental impacts, indirect public costs, and implications for employment, innovation, and economic growth, while diverse stakeholder values and interests further complicate these considerations (Rechtschaffen et al. 2009). Urban residents frequently misinterpret the relationship between safety and lighting levels, leading to an uncontrolled proliferation of artificial lighting in a misguided effort to enhance safety. In contrast, rural residents typically prioritize the preservation of natural nightscapes (Stone 2017). These complexities, further highlighted by the challenges of enforcing light pollution regulations due to the mobility of fixture owners or tenants (Cao et al. 2022), underscore the need for careful consideration when selecting and implementing environmental regulations, ensuring that they are both effective and feasible.

To attain an optimal balance for the above example, further studies are needed. A critical component in such studies is cost–benefit analysis, weighing the regulation's benefits

against its associated costs. Although cost–benefit analysis is pivotal in regulation design (Sunstein 2002), quantifying certain costs and benefits can be challenging. Balancing diverse stakeholder priorities often requires complex negotiation and compromise (Bardach and Kagan 1982). As illustrated in Britain's environmental strategy "This Common Inheritance" and the U.S. Clean Air Act, the focus of regulation need not be on exact limits but rather on establishing acceptable societal standards (Ploetz 2002).

Regular regulatory reviews incorporating the latest research findings can guide the refinement of the relevant environmental protection standards. For example, the robust link between air quality and light pollution (Wallner and Kocifaj 2023), or the impact of spectral tuning of LEDs on attracting insects (Kamei et al. 2021), underlines the importance of integrating scientific progress into regulatory updates. Research has also found that meteorological conditions, such as aerosol optical depth, asymmetry parameters, single scattering albedo, direct uplight, surface reflectivity, and aerosol scale height, on night sky brightness in regions are affected by ALAN, suggesting an inter-control between air quality and light pollution (Wallner and Kocifaj 2023). This provides valuable insight into the need for robust regulations, like command-and-control measures, which have proven effective in reducing air pollutant emissions, while soft law approaches have shown limited impact (Steinebach 2022).

The polluter-pays principle is one of the pillars of environmental regulation (Purdue 1991). Traditionally, this principle has been applied to the users of light (i.e., those who generate light pollution by using lighting fixtures), given that the existing regulations focus mainly on the side of the user (i.e., use standards, emission standards). However, research shows that over 40% of lighting solutions failed to meet certain assessment criteria for lighting conditions, light pollution, and lighting energy efficiency, according to EN 12464-2, EN 12301, CIE 150, and other relevant standards (Pracki and Skarżyński 2020). If lighting fixture manufacturers contribute to light pollution by producing fixtures that are more likely to cause such pollution, one could argue that they are also "polluters" in a sense. Therefore, this principle could be used to suggest that manufacturers should bear some of the costs of mitigating light pollution, potentially through regulations requiring them to produce more environmentally friendly fixtures or to contribute to light pollution reduction initiatives. The feasibility, progress, and effect of implementing this principle in the manufacturing sector are worth studying in the years to come.

5. Conclusions

Our investigation into the legal systems and regulatory approaches of the six jurisdictions has illuminated the complex relationship between legal instruments and environmental protection. The study revealed a pattern where civil law jurisdictions, like those of Shanghai and Seoul, typically favor dedicated legislation, while common law jurisdictions, such as New York and London, often utilize a bolt-on approach. However, we also underscore that these tendencies are not absolutes, and that there can be variations within both legal systems.

While dedicated legislation with a metrics-based system offers a comprehensive and proactive control of light pollution, its potential for triggering unintended consequences, such as overuse in non-regulated times and areas, and financial burdens on businesses and individuals, cannot be ignored. The balance between certainty and flexibility in regulation is a delicate one and requires nuanced understanding and careful evaluation of their merits and limitations. The comparative analysis of various metrics-based controls reveals that the regulatory framework of Shanghai is relatively comprehensive and stringent. However, this metrics-based approach raises questions about whether operators can absolve themselves of potential liability for light emissions if the emissions still adversely impact others. This issue warrants further study, particularly when exploring whether nuisance law, which employs broader concepts rather than a fixed set of metrics, may offer a more effective solution. The study highlights the need for regular regulatory reviews that incorporate the latest scientific findings. The evolving nature of our understanding of light pollution, its

impacts, and the best mitigation strategies underlines the need for adaptable and responsive regulatory frameworks. Moreover, the diverse stakeholder values and interests further complicate the implementation of effective and acceptable regulation.

Finally, we propose that future research should examine the potential for applying the polluter-pays principle to lighting fixture manufacturers. Such an approach might shift some of the burden of mitigating light pollution to those who produce more polluting fixtures, aligning the economic incentives with environmental goals. As we continue to illuminate our world, we must ensure that such illumination does not unnecessarily pollute our environment or compromise public health and biodiversity.

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