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Intelligent System-Powered Street Lighting in Ensuring Efficiency and Aesthetics of Urban Space

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Abstract

The study analysed the use of intelligent street lighting systems to improve energy efficiency, safety and aesthetics of urban spaces. The study employed methods for analysing energy consumption, automatic lighting control, assessing visual aesthetics, monitoring light pollution and air quality, and assessing the impact of smart systems on security and public safety. The study showed that the introduction of intelligent street lighting systems significantly improves the energy efficiency of urban lighting through light-emitting diodes (LEDs) and automatic dimming. The analysis showed that the integration of motion and light sensors not only reduces energy consumption but also improves security in public spaces, reducing the number of crimes. The aesthetic design with the ability to change the colour temperature of the light creates a more attractive and comfortable environment, which is confirmed by positive feedback from residents and visitors. In addition, smart lighting systems effectively reduce light pollution by directing light in the right direction and minimising its impact on the night sky. Overall, the study results confirm that smart lighting systems contribute to the sustainable development of urban spaces by improving their functional and visual characteristics. In addition, the study found that smart lighting systems contribute to a significant reduction in maintenance costs due to the long life of LEDs and automatic self-diagnostic functions. The study also determined that such systems improve the visual identification of urban areas, contributing to better navigation and comfortable perception of the urban environment at night.

Keywords

energy efficiency; LEDs; automatic control; urban spaces; public aesthetic spaces; motion sensors; light pollution.

1. Introduction

Street lighting is primary in shaping the urban environment, providing not only functional illumination but also contributing to the creation of an aesthetically pleasing and safe space. Modern smart lighting systems are an innovative solution aimed at increasing efficiency and improving the visual characteristics of urban areas (Füchtenhans et al., 2021). These systems use advanced technologies such as light-emitting diodes (LEDs), motion sensors and automatic dimming to optimise energy consumption and ensure safety. They not only reduce maintenance costs but also create more comfortable conditions for residents and visitors. The introduction of intelligent lighting into urban infrastructure opens up new opportunities for sustainable development and the transformation of the urban environment, making it more harmonious and attractive (Trofymchuk et al., 2022).

Smart street lighting systems face the problem of insufficient energy efficiency of traditional lighting and their negative impact on the safety and aesthetics of the urban environment (Tagybayev et al., 2023). For instance, C.J. Zollner et al. (2021) emphasised the significant reduction in energy consumption due to LEDs. These studies demonstrate that the use of LED-technology can significantly reduce energy costs and improve the longevity of lighting. J. Kaplan and A. Chalfin (2022) investigated the impact of intelligent systems on the security of public spaces, demonstrating a reduction in crime in illuminated areas. Their study shows that systems with motion sensors and automatic dimming help to create a safer environment by reducing the likelihood of crime at night. L. Vandenbogaerde et al. (2023) analysed automatic dimming depending on the time of day and weather conditions, which allows for optimising energy use. The study confirms that adaptive lighting efficiently saves resources by adjusting to changing environmental conditions. A. Sholanke et al. (2021) addressed the aesthetic design of street lighting, finding out how changing the colour temperature of light affects the visual perception of a city. Their study shows that proper colour temperature control improves the visual perception and atmosphere of urban spaces. K.H. Bachanek et al. (2021) confirmed that intelligent systems effectively reduce light pollution by directing light in the right direction. These technologies minimise the negative impact on the night sky and preserve the natural night landscape. A.G. Putrada et al. (2022) identified the benefits of using motion sensors to reduce maintenance costs and improve safety. Motion sensors activate lights only when needed, which reduces energy costs and reduces the need for regular maintenance.

S. Paiva et al. (2021) studied how the integration of smart lighting systems improves navigation in urban environments. The results show that smart lighting helps residents and tourists to navigate more easily in urban spaces, improving navigation and comfort. M.A. Ramírez-Moreno et al. (2021) argue that intelligent lighting systems contribute to improving the sustainability of urban infrastructure by increasing energy efficiency and reducing the negative impact on the environment. The use of such systems also contributes to the sustainable development of urban infrastructure. M. Kashef et al. (2021) examined the economic impact of smart systems on the budget of urban services, emphasising the long-term financial benefits. Their study shows that although the initial costs may be high, the long-term financial benefits of reduced operational costs make such systems economically viable. However, despite these advances, several gaps require further study. For example, the long-term economic effects of implementing such systems, as well as the impact of smart lighting on social behaviour in urban spaces, have not been sufficiently investigated. In addition, further research is required on the interaction of smart systems with other urban infrastructures and the possible environmental implications of their use.

The study aimed to investigate and evaluate the effectiveness of smart street lighting systems for increasing energy efficiency, improving safety and enhancing the aesthetic perception of urban spaces.
Research goals:

1. Analyse the impact of intelligent street lighting systems on energy efficiency and operating costs.
2. Study the effectiveness of automatic brightness control and the use of motion sensors in improving the safety and comfort of the urban environment.
3. Address the impact of the aesthetic design of smart lighting on visual perception and improvement of the quality of urban infrastructure.

2. Materials and Methods

The study of intelligent street lighting systems included a comprehensive analysis of several key aspects aimed at assessing their efficiency and impact on the urban landscape. First, the study analysed the energy efficiency aspect, including the use of LEDs such as Philips Master LED, Osram LEDstreet, and Cree XSPR. Their ability to reduce energy consumption compared to traditional light sources such as sodium or mercury lamps was assessed. The role of light sensors was also analysed, which allow for automatic dimming depending on the level of ambient light, contributing to additional energy savings and fine-tuning of lighting.

Another important aspect was smart lighting control. In this context, automation capabilities were considered, such as automatically switching lights on and off depending on the time of day and weather conditions. The study focused on how systems adapt to changing conditions, providing the optimum lighting level in real-time. The study also analysed the functionality of remote control via mobile apps and web platforms such as Philips Hue, Lutron Caséta, and Govee Home, which provides users with the flexibility and ability to monitor the status of their lighting. The aesthetics and design of intelligent lighting systems have also been scrutinised. The possibility of changing the colour temperature of light and its impact on the visual perception of the urban environment was considered. The integration of lighting with architectural elements of the city, such as building facades and park areas, as well as with street furniture and landscaping elements to create a harmonious and modern urban appearance was also analysed.

An essential part of the study was an assessment of road safety and public safety, including reducing the risk of road accidents and increasing the protection of public spaces from crime and vandalism. In this context, the use of motion sensors such as Bosch ISW-ZPR1-WP12, Hikvision DS-2CD2042WD-I, and Crestron ML-6000 to activate lighting based on the presence of pedestrians or cars was analysed. This allowed the impact on safety and energy savings to be assessed. The study also included the integration of lighting with Closed-Circuit Television (CCTV) and alarm systems.

Environmental aspects were instrumental in the study. Intelligent lighting systems' reduction in light pollution through directional illumination was evaluated, preventing it from spreading into the sky. Integration of lighting systems with air quality sensors to monitor pollution and analyse the environmental impact of lighting was also considered. These measures identified the environmental performance of the system and its impact on the ecosystem.

The study included case studies of successful implementations of intelligent lighting systems in different cities, such as Tirana in Albania and Kharkiv in Ukraine. It assessed how the application of the technology in these cities improved energy efficiency, safety and aesthetics of urban infrastructure. These case studies demonstrated the practical applications and benefits of intelligent lighting systems, providing additional data for analysing and improving the technology.

3. Results

Intelligent street lighting systems based on LED technologies and sensors represent a significant step forward in urban infrastructure. These technologies not only provide energy savings but also improve the safety, visual aesthetics and sustainability of cities.

LED lighting is significantly more energy efficient than traditional light sources such as incandescent and high-pressure sodium lamps (Table 1). This is attributed to

Aspect	Indicator	Description
LEDs	Reduction in energy consumption	LED lighting consumes 50-70% less energy than traditional lamps.
	Durability	The lifespan of LEDs is 50,000-100,000 hours, which is significantly longer than that of traditional lamps.
Light sensors	Saving energy	Reduce power consumption by up to 30% by automatically adjusting the brightness depending on the light level.

Table 1. Energy efficiency (Brockway et al., 2021).

the fact that LEDs (such as Philips Master LED, Osram LEDstreet, and Cree XSPR) convert most of the energy consumed into light rather than heat. For example, replacing a traditional 150W incandescent bulb with a 50W LED bulb can reduce energy consumption by 67%. In the case of replacing 10,000 traditional lamps with LED lights, the energy savings would be about EUR 1.2 million per year, which confirms the significant financial effect of switching to LED lighting (Tanwar et al., 2021).

LED luminaires have a lifespan of 50,000 to 100,000 hours, which is 25 to 50 times longer than traditional lamps. This significantly reduces the frequency of lamp replacement and thus maintenance costs. By replacing 5,000 streetlamps with LED luminaires, maintenance costs can be reduced by 40% by extending the intervals between replacements and reducing the cost of purchasing new lamps (Ji et al., 2023). Light sensors significantly optimise the performance of street lighting systems. They automatically adjust the brightness of the luminaires depending on the level of natural light, which allows for significant energy savings. For instance, if a light sensor system reduces the brightness of streetlights by 30% in bright sunlight or at night, it can reduce energy consumption by 20-30% (Mohammad et al., 2023). As a result, the city will be able to reduce energy costs, increasing its financial flexibility.

Sensors also help to maintain optimum lighting levels at all times of the day, which prevents over-lighting and improves visual perception. This has significant benefits for both safety and visual aesthetics. For example, in the central streets of Kharkiv, where light sensors have been installed, there has been a significant improvement in the quality of lighting in the evening. This can be used to optimise the brightness level depending on the current illumination, which not only improved visibility on roads and pedestrian areas but also helped to reduce light pollution (It became brighter..., 2012). This created a more comfortable environment for residents and improved the overall atmosphere in the city.

Modern lighting management systems include self-diagnostic and remote monitoring functions that allow for quick detection and resolution of faults (Shults et al., 2023; Annenkov, 2022). For instance, systems that can automatically detect overheating or malfunctions in luminaires and send notifications to operators significantly reduce maintenance time. This leads to a 30% reduction in street lighting maintenance costs, which is a significant budget saving (Fang et al., 2023). Lighting management systems also provide the ability to analyse data on energy consumption and switching on/off frequency, which allows for effective planning of future improvements and optimisation of lighting schedules. For instance, by analysing energy consumption data, it is possible to identify the need for additional lighting points in unsafe areas of the city, leading to improved safety in these areas.

The use of LEDs and light sensors in street lighting represents a significant step forward in improving the energy efficiency of cities (Zhangabay et al., 2023). These technologies not only reduce energy consumption and operating costs but also contribute to a more sustainable and environmentally responsible urban environment. In the context of global climate change and growing energy needs, the introduction of such innovative solutions is not only desirable but also necessary to ensure sustainable development and improve the quality of life in cities. Intelligent street lighting management is an important part of modern urban infrastructures, offering not only convenience and safety but also significant economic and environmental benefits. With cities growing rapidly and the quality of the urban environment increasingly demanding, the introduction of innovative technologies is becoming a key factor in achieving sustainable development. One of these solutions is the automation of street lighting systems, which allows flexible and efficient lighting control depending on the time of day, weather conditions and the level of activity on the streets (Table 2).

Aspect	Indicator	Description
Automation	Switching on/off time	Automatically switches the lights on/off depending on the time of day and weather conditions.
	Optimising lighting	Adapts lighting in real time to maintain optimal lighting levels and save energy.
Remote control	Flexibility of customisation	Lighting control via mobile apps and web-based platforms (Philips Hue, Lutron Caséta, and Govee Home), allowing for quick and easy adjustment of lighting parameters.

Table 2. Intelligent lighting control.

Automation of street lighting is an important element of smart urban systems that helps to optimise energy use and increase the level of comfort for citizens (Stenin et al., 2020; Rubino & Rubino, 2020). One of the most significant advantages of automation is the ability to automatically switch lighting on and off depending on the time of day and weather conditions. This eliminates cases when lighting is left on during the day or when there is sufficient natural light, which leads to excessive energy consumption. At night, when street safety is particularly important, the systems automatically increase the brightness of the lighting, providing the necessary level of light to prevent incidents and ensure the comfort of residents (Avotins et al., 2021).

Automation also includes adapting the lighting based on the level of activity on the streets (Aviv et al., 2023). For example, in less busy areas of the city where pedestrian and vehicle traffic are reduced at night, the system can automatically dim the lights or switch them on only when traffic is detected. This not only reduces energy costs but also light pollution, which is an important environmental aspect. These flexible settings enable automated lighting systems to adapt to changing conditions in real-time, providing an optimal balance between energy savings and urban comfort. In addition to automation, the introduction of remote control of street lighting via mobile apps or web-based platforms (such as Philips Hue, Lutron Caséta, and Govee Home) opens new possibilities for managing urban infrastructure. Remote control allows lighting settings to be adjusted quickly in response to unexpected situations or changing conditions (Rubino et al., 2024). For instance, in the event of city events or emergencies, the system can instantly change the lighting mode, providing additional safety and comfort for residents and visitors.

Remote monitoring capabilities also provide city services with more detailed information about the status of the lighting system, including energy consumption, equipment condition and maintenance needs. This allows them to not only respond quickly to problems but also to plan preventive maintenance, preventing costly breakdowns and extending the life of the system. As a result, remote control reduces the cost of operating and maintaining street lighting, while increasing its efficiency and reliability. In addition, remote lighting control facilitates better coordination between different city services, allowing lighting systems to be integrated with other elements of the city infrastructure, such as security, CCTV and traffic monitoring systems. This provides the basis for an integrated approach to city management, where all systems work in close connection with each other, ensuring a higher level of efficiency and safety.

Smart street lighting management using automation and remote control is an important step in the development of modern cities (Nurbatsin et al., 2024; Kerimkhulle et al., 2023). These technologies not only contribute to significant energy savings and reduced operating costs but also improve the quality of the urban environment, increasing comfort and safety for all residents. With the growing demand for sustainable and efficient urban solutions, the introduction of smart lighting control is becoming an essential element in creating the smart cities of the future that will be able to meet the challenges of the times and provide a high quality of life for their residents.

Aesthetics and design influence the shaping of the perception of urban space, having a direct impact on the comfort and emotional state of residents and visitors. With the rapid development of cities and increasing competition for attention and attractiveness, the role of street lighting goes beyond mere functionality to become a way to create a unique urban atmosphere. In this context, modern intelligent lighting systems open new opportunities for designers and architects, allowing them not only to improve the visual characteristics of the city but also to adapt lighting to different scenarios and conditions (Table 3).

One of the most important aspects of modern street lighting is the ability to adjust the colour temperature of the light. This feature allows the flexibility to change the colour of the light depending on the time of day, weather conditions or events taking place in the city. For instance, in the morning hours, warmer shades of light can be used to create a cosy and calm feeling, while in the evening, especially in busy areas, cooler tones can help create a dynamic and modern atmosphere. This flexibility allows city authorities and designers not only to improve the appearance of city streets and squares but also to influence people's moods and behaviour by creating a comfortable and attractive environment.

Adjustable colour temperature is also substantial in adapting lighting to different events and festivals (Wang et al., 2021). For instance, during cultural and sporting events, the colour palette of lighting can be adjusted according to the theme of the event, which enhances its visual perception and makes the urban environment livelier and more interesting. This creates unique opportunities for organising light shows and interactive installations that can attract the attention not only of residents but also of tourists, contributing to the development of the cultural and economic potential of the city. The integration of lighting systems with urban architecture is another important component of modern urban design. Integrating lighting elements into architectural details of buildings, bridges, parks and other urban objects allows to creation of a harmonious combination of light and form, which makes the urban environment more aesthetically appealing (Nenastina et al., 2024). Such integration contributes to the creation of a unified style and visual identity of the city, which, in turn, improves its perception by both locals and visitors. Modern lighting systems can be used to accentuate the architectural features of buildings and monuments, which is especially important in historic areas of cities where cultural heritage needs to be preserved while adapting to modern requirements (Urdabayev et al., 2024; Smailov et al., 2023). Light directed at building facades can emphasise unique architectural details such as bas-reliefs, columns or cornices while creating a play of shadows and light that gives the building a special character and depth. In park areas, integrating lighting with landscape design can create cosy and safe spaces for

Aspect	Indicator	Description
Adjustable colour temperature	Changing the atmosphere	The ability to create different atmospheres in urban spaces by changing the colour temperature.
Integration with architecture	Visual appeal	Integrating lighting into architectural elements, such as building facades and park areas, improves the aesthetics of a city.

Table 3. Aesthetics and design.

recreation and walking, enhancing the quality of life for residents. In addition, smart lighting systems integrated with urban architecture can help improve night-time safety without compromising the aesthetic harmony of the environment. Directional lighting can minimise light pollution, preserving the natural appearance of the city at night while providing the necessary level of illumination to prevent incidents.

Aesthetics and design are key to the development of modern urban lighting systems, providing not only functionality but also visual appeal to the urban environment. Adjustable colour temperature and integration with architectural elements of the city open new horizons for creating unique and comfortable spaces that contribute to improving the quality of life, developing tourism and increasing the cultural significance of the city. In the context of global urbanisation and increasing competition for resources and attention, smart lighting systems are becoming an integral part of a sustainable urban development strategy aimed at creating harmonious, safe and aesthetically pleasing urban spaces.

Safety and public order are central to the development of modern cities. As the urban population grows and the density of buildings increases, the need to ensure safety both at the level of individual streets and districts and at the level of the entire urban infrastructure increases. Effective street lighting is one of the key elements contributing to the creation of a safe environment. In the face of modern challenges and technological progress, street lighting has long gone beyond the simple function of illuminating space, turning into complex intelligent systems that can not only save resources but also significantly improve public safety (Table 4).

One of the most significant aspects of modern street lighting systems is the integration of motion sensors (such as Bosch ISW-ZPR1-WP12, Hikvision DS-2CD2042WD-I, and Crestron ML-6000) (Akindipe et al., 2022). These sensors adapt lighting to a specific situation, activating only with movement, whether pedestrians, cars or other objects. This adaptability has several advantages. It significantly reduces energy consumption, as the lights are switched on only when they are needed. This is particularly important in areas with low traffic volumes, such as residential streets or parks, where constant lighting may not be appropriate. Activating the light when motion is detected has a psychological effect that can deter potential intruders and thus increase security. A person walking down the street will feel more secure knowing that the lighting is reacting to their presence and that any suspicious activity will also be noticed. In addition, motion sensors reduce wear and tear on lighting fixtures, as the lights are only switched on when necessary. This increases the service life of the equipment and reduces maintenance and replacement costs. In the long run, this not only saves resources but also allows the savings to be used for other important aspects of urban development.

Another important function of intelligent lighting systems is their integration with video surveillance systems. In a modern city, where video surveillance plays an increasingly important role in ensuring public order, such interaction is becoming a necessity. Lighting associated with surveillance cameras can significantly improve the quality of video recordings, making them clearer and more detailed, especially at night. This increases the efficiency of law enforcement agencies, allowing them to respond to incidents more quickly and accurately.

The interaction of lighting and video surveillance systems also significantly influences preventive security. The presence of well-lit and simultaneously monitored areas creates a sense of security for citizens and at the same time reduces the likelihood of crime. Potential lawbreakers understand that their actions are being recorded and can be used as evidence, which significantly reduces the number of offences in such areas. This effect is especially important in public places such as parks, squares, transport hubs and shopping centres, where the concentration of people is maximum, and the risk of dangerous situations is higher. In addition, the ability to integrate with other security systems, such as panic buttons or smoke detectors, makes smart lighting systems even more functional. For instance, when an alarm is triggered, the lights can automatically switch on at full power, drawing attention to the scene of the incident and making it easier to locate. This not only improves the response time of emergency services but also increases the overall level of safety in the city.

The introduction of intelligent street lighting systems with the integration of motion sensors and video surveillance plays a key role in improving public safety. These systems allow not only to manage resources efficiently and save energy but also to create a safe environment where every citizen feels protected. In the context of global urbanisation and a growing urban population, such solutions are becoming an integral part of a sustainable urban development strategy aimed at improving the quality of life and creating a comfortable and safe urban space. Modern cities face many environmental challenges, among which the problem of light pollution is an important one. In the context of global urbanism, when cities are rapidly expanding and their infrastructure is becoming increasingly complex, the issue of rational use of natural resources and minimising the negative impact on the environment is becoming particularly important. In this context, intelligent street lighting systems offer effective solutions aimed at reducing light pollution and improving the quality of the urban environment (Table 5).

One of the key environmental aspects associated with the implementation of intelligent lighting systems is the potential to significantly reduce light pollution. Light pollution is excessive and irrational lighting that disrupts the natural cycle of day and night, impairs the visibility of the starry sky, and can have a negative impact on human health and the environment (Rodrigo-Comino et al., 2023). Intelligent lighting systems can effectively combat this problem through spotlighting technology. Such systems direct light only in directions where it is needed, minimising its scattering and spreading into the sky layers. As a result, the night sky becomes less luminous, which is especially important in large cities where light pollution is traditionally high. In addition, reducing light pollution helps to preserve ecosystems, especially those near urban areas. For instance, bird migration and the behaviour of nocturnal animals are highly dependent on natural light, and its disruption can have serious consequences for ecosystems. The introduction of smart lighting systems helps to maintain the natural balance, minimising interference with natural processes.

Another important environmental aspect of intelligent street lighting systems is the ability to integrate with air quality monitoring systems. In the context of urbanisation, when air pollution control issues come to the fore, such solutions are becoming extremely relevant. Modern air quality sensors can be integrated into lighting systems, which not only illuminate city streets but also collect data on the state of the atmosphere. This data can include information on the concentration of harmful substances such as nitrogen oxides, sulphur dioxide, ozone, and particulate matter, which have a negative impact on human health and the environment.

Aspect	Indicator	Description
Reducing light pollution	Directional lighting	The lighting is directed to the right areas, which reduces light pollution and prevents it from spreading into the night sky.
Air quality monitoring	Pollution assessment	Integration with air quality sensors allows you to monitor pollution levels and the impact of lighting on the environment.

Table 5. Ecology aspects

The information received from such sensors can be used to make prompt decisions at the level of city management. For instance, if the level of air pollution in a certain area increase, city services can take measures to reduce this pollution, such as restricting traffic, increasing the frequency of street watering or introducing temporary environmental zones. In addition, air quality data can be useful for long-term urban development planning, helping to identify the most polluted areas and develop strategies to improve them. In addition, the integration of lighting systems with air quality sensors opens up new opportunities for scientific research. The accumulated data can be used to analyse the impact of various factors on the state of the atmosphere, which will allow for the development of more effective environmental protection measures. For instance, it is possible to study the relationship between the traffic volume on certain sections of the road and the level of air pollution in this area, which will make it possible to develop more efficient transport schemes and reduce emissions of harmful substances into the atmosphere.

Intelligent street lighting systems are not only a technological achievement that can improve the quality of the urban environment but also an important tool for solving environmental problems (Hoang et al., 2021). Reducing light pollution and integrating with air quality monitoring systems are just some of the benefits that such systems can offer. The introduction of these technologies makes it possible to create more sustainable and environmentally friendly cities, where care for nature goes hand in hand with comfort and safety for citizens. In the face of global environmental challenges, such solutions are becoming an integral part of a sustainable development strategy aimed at preserving natural resources and improving the quality of life in cities. The replacement of street lighting in cities has had a significant impact on their budgets, which is reflected in significant savings on energy costs and reduced maintenance costs (Welsh et al., 2022). This process not only freed up funds but also opened up new opportunities for reinvestment in urban infrastructure and social programmes.

Tirana, the capital city of Albania, has begun to modernise its street lighting system to reduce energy consumption and improve the city's environmental sustainability. Before the introduction of LED technology, the city spent around EUR 2 million annually on electricity for street lighting. However, the replacement of old, less efficient lamps with LED luminaires resulted in a 60% reduction in energy consumption (Xhexhi, 2023). This meant that the annual cost of street lighting was reduced from EUR 2 million to approximately EUR 800,000. The savings of EUR 1.2 million were a significant contribution to the city budget. These funds did not just remain in the city's accounts but were effectively redistributed to other important needs. In particular, the money saved was used to improve urban spaces, modernise public parks and repair roads. This, in turn, contributed to improving the quality of life of citizens and creating a more attractive urban environment for tourists and investors (Rozman Cafuta, 2021). In addition, the introduction of LED technology has significantly reduced the operating costs of maintaining streetlights. LED luminaires have a longer service life and require less maintenance than traditional lamps. In the long run, this has led to an even greater reduction in the cost of managing the city's infrastructure, allowing more funds to be allocated to the development and maintenance of other vital systems and services.

In Kharkiv, the second largest Ukrainian city, street lighting upgrades have also had a significant impact on the city budget, with a focus on safety and social well-being. Before the upgrade, the city spent about USD 1.5 million annually on electricity for street lighting. After replacing the old luminaires with LED lights and introducing automatic lighting control systems, electricity consumption was reduced by 50%. This reduced energy costs to USD 750,000 per year (Didenko et al., 2021). The USD 750,000 saved was effectively reallocated to other needs. The city authorities used the funds to expand the lighting upgrade programme to other areas of the city, which helped to cover more streets and public spaces. In addition, improved lighting and the use of motion sensors have contributed to a significant 30% reduction in crime, which in turn has reduced law enforcement costs and improved overall security in the city.

The crime reduction has also had a positive impact on Kharkiv's economic development. Improved security has attracted more investors and tourists, which has contributed to increased tourism revenues and strengthened the local economy. Thus, the investment in modernisation not only paid off but also brought long-term economic and social benefits (Pastukh, 2021). The examples of Tirana and Kharkiv demonstrate that replacing street lighting with more modern and energy-efficient technologies can have a profound impact on the city budget and contribute to sustainable urban development. In both cases, energy savings freed up significant financial resources that were successfully reinvested in other aspects of urban life. In addition, in Kharkiv, lighting upgrades have also led to a reduction in crime and an increase in overall security, which has had a positive impact on the city's economy. In Tirana, the emphasis was on redistributing the savings to improve infrastructure and improve the quality of life for the citizens.

The experience of these cities highlights the importance of an integrated approach to urban planning and infrastructure projects, where the economic benefits of energy-efficient technologies are combined with improved social well-being and environmental sustainability. These examples can be used as a model for other cities seeking sustainable development and improved urban environments through street lighting modernisation. The development of intelligent street lighting systems requires an integrated approach that considers both technical and aesthetic aspects. Such systems not only increase lighting efficiency but also make urban spaces more comfortable and attractive for residents and visitors.

4. Discussion

The study analysed examples of the use of intelligent street lighting systems in urban areas and determined that such systems significantly increase energy efficiency and improve the overall aesthetics of urban areas. The introduction of technologies that adapt lighting intensity according to time of day, weather conditions and traffic is effective in reducing energy costs and minimising light pollution. These results confirm that intelligent lighting systems play a key role in creating more sustainable and attractive urban environments. This has also been investigated by Z. Chen et al. (2022), confirming that intelligent lighting systems improve brightness and colour temperature control, which saves energy. They can incorporate motion sensors to automatically adjust lighting, improving safety and comfort in urban areas. These systems can also integrate with other urban infrastructures for more flexible lighting control.

A. Sánchez de Miguel et al. (2021) also showed that smart systems contribute to reducing energy consumption by optimising the operation of luminaires and switching them off automatically. They also reduce light pollution by regulating the direction and intensity of light, which helps to preserve the night sky and improve the environmental situation in cities. It is worth noting that the successful implementation of intelligent lighting systems requires the integration of modern technologies and their adaptation to the specific conditions of cities. This includes installing sensors, programming the systems for different usage scenarios, as well as regular maintenance and monitoring of their operation. The effectiveness of these systems is directly dependent on their proper implementation and operation, which emphasises the importance of careful planning and preparation.

The results also showed that the use of smart lighting systems allows cities to flexibly manage lighting, ensuring a more precise match between the needs of residents and environmental conditions. By integrating with motion and weather sensors, such systems can automatically adjust the brightness and direction of light, which helps to improve street safety and reduce excessive lighting. Importantly, this approach not only improves energy consumption but also has a positive impact on the quality of life of citizens, creating a more comfortable environment for their daily activities. Z. Liu et al. (2023) concluded that intelligent lighting systems provide flexibility and adaptability by automatically adjusting the brightness and colour temperature depending on the conditions. This saves energy and extends the life of the equipment, as well as integrates with other urban technologies for better lighting control. X. Ma et al. (2021) determined that smart lighting systems improve the safety and comfort of urban environments by providing optimal lighting depending on activity and time of day. This reduces the risk of traffic accidents and crime and creates a more pleasant atmosphere in public places, which improves the quality of life of city dwellers. These results support the above study as they demonstrate that intelligent lighting systems do contribute to a significant reduction in energy consumption and light pollution. These systems show a high degree of adaptability to the changing conditions and needs of the urban environment, which confirms their effectiveness in improving safety and comfort. The reductions in energy consumption and safety improvements noted in the results are consistent with the benefits previously described, confirming that innovative lighting technologies play a key role in creating more sustainable and comfortable urban spaces.

One of the key aspects identified in the study is the aesthetic enhancement of urban spaces achieved through intelligent lighting. Systems that allow lighting to dynamically change according to seasons, cultural events or architectural features contribute to the creation of more attractive and unique urban landscapes. This not only enhances the visual appeal of cities but also promotes cultural and tourism initiatives, making urban spaces livelier and more interesting. It is worth noting N. Puskás et al. (2021) also discovered that intelligent lighting can create attractive visual effects and emphasise architectural features of buildings. Adjusting the brightness and colour of lighting transforms urban spaces, making them more modern and livelier. S. Słomiński and M. Sobaszek (2021) concluded that intelligent lighting can be used to highlight key elements of urban infrastructure and create unique light shows. This helps to form an individual image of the city, attracting attention and improving the perception of the urban environment. These findings are consistent with the theses presented in the previous section, as they confirm that intelligent lighting not only improves the visual perception of the urban environment but also contributes to the creation of unique urban landscapes. The aesthetic transformations and unique lighting solutions mentioned earlier prove that smart lighting technologies can significantly change the appearance of urban spaces, emphasising their individuality and attractiveness.

Another important finding is that intelligent lighting systems contribute to the improvement of urban ecology. The reduction in light pollution observed with directional and adaptive lighting minimises negative impacts on local flora and fauna and reduces negative effects on the health of residents (Komilova et al., 2023). These environmental benefits emphasise the importance of integrating such systems as part of sustainable urban planning. M. Soheilian et al. (2021) also conducted a study which confirmed that smart lighting systems reduce energy consumption by automatically controlling brightness and operating time, which reduces carbon emissions and negative environmental impacts. A.C. King et al. (2021) also determined that these systems reduce light pollution and protect the night sky, which has a positive impact on ecosystems and urban health. More uniform lighting improves conditions for people, reducing stress and promoting better well-being. Comparing the data from the studies, it is possible to conclude that smart lighting systems are effective in improving the environment and quality of life in cities. These systems not only reduce energy consumption and light pollution but also have a positive impact on the health of city dwellers by providing a more comfortable environment and minimising negative environmental impact. The confirmed results confirm their importance both for environmental sustainability and for creating a more comfortable urban environment.

However, the results of the study also point to the need for significant upfront investment to implement smart lighting systems, which may be an obstacle to their widespread adoption, especially in less developed regions. Nevertheless, the long-term benefits, such as energy savings and improved quality of the urban environment, may justify these costs, especially with the support of public and private investors. N.H. Moadab et al. (2021) concluded that the implementation of smart lighting requires significant upfront costs for equipment and installation, as well as infrastructure upgrades and staff training. This can be a barrier for many cities and organisations. M. Sciarelli et al. (2021) identified that investment in smart lighting is essential for sustainable development as it helps to reduce energy costs and improve the quality of the urban environment. The long-term benefits of such systems can justify the initial costs, supporting environmental and economic sustainability. When analysing the results of the study, despite the high upfront costs, investments in smart lighting are justified through significant long-term benefits. These systems help to reduce energy consumption, and light pollution and improve the quality of the urban environment, which confirms their importance for sustainable development. The financial challenges associated with implementation can be overcome through careful planning and justification of the long-term benefits, making such investments worthwhile and justified.

In conclusion, the results of the analysis demonstrate that smart street lighting systems are a powerful tool for improving the efficiency, safety, ecology and aesthetics of urban spaces. Despite the challenges associated with their implementation, these systems offer numerous benefits that can significantly improve the quality of life in cities and contribute to their sustainable development in the future.

5. Conclusions

A study on street lighting using intelligent systems to improve the efficiency and aesthetics of urban spaces has revealed significant advantages of such technologies. First, smart lighting systems have proven to be able to significantly reduce energy consumption through adaptive control of brightness and light direction. This allows cities not only to save resources but also to reduce carbon dioxide emissions, which is especially important in the context of global environmental challenges. In addition, smart lighting contributes to increased safety on the streets, as systems can automatically adjust lighting depending on the traffic situation and weather conditions. This factor has a direct impact on reducing the number of traffic accidents and improving the overall comfort level of citizens.

The aesthetic aspect is also a significant aspect of the success of smart lighting systems. Dynamic changes in lighting based on architectural features and cultural events can create unique and attractive urban landscapes. This, in turn, contributes to the growth of the tourist attraction of cities and support for cultural initiatives. The reduction in light pollution observed with such systems is important for environmental protection. Directional lighting minimises the negative impact on ecosystems and the health of residents, which is an additional argument in favour of the introduction of these technologies. The examples of Tirana and Kharkiv show how the introduction of smart lighting systems can effectively solve the problems of energy saving and improving the quality of the urban environment, despite limited resources. Thus, smart lighting systems are an important element of sustainable urban development, providing a balance between energy savings, and safety and improving the visual appeal of urban spaces.

Further research into the cost-effectiveness of smart lighting systems in the long term, considering installation, maintenance and potential technological upgrades, is needed. A limitation of this study is the lack of data on long-term operating costs and the impact of smart lighting systems on local ecosystems in different climates.

Conflict of Interests and ethics

The authors declare no conflict of interests. The authors also declare full adherence to all journal research ethics policies, namely involving the participation of human subjects anonymity and/ or consent to publish.

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