Journal of Environment and Earth Science
ISSN 2224-3216 (Paper) ISSN 2225-0948 (Online)
Vol.14, No.6, 2024

Photoluminescent Materials: A Sustainable Solution for Eco-Friendly Design

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Abstract

Photoluminescent materials absorb energy when exposed to light and subsequently re-emit this energy at a different wavelength by glowing in the dark. These properties contribute to a variety of functional and aesthetic benefits, including safety and visibility, energy efficiency, aesthetic enhancement, guidance and marking, sustainability. Due to their wide range of applications, photoluminescent materials play a significant role in eco-friendly design and engineering projects. They offer considerable advantages in both superstructure and infrastructure applications and landscape design projects, as well as in structural and infrastructure applications within civil engineering, thanks to their light absorption and nighttime glowing characteristics. This study examines the use of photoluminescent materials, addressing the benefits of this innovative material in terms of aesthetics, safety, and functionality through practical application examples. The study highlights the contributions of photoluminescent materials in terms of innovative solutions, sustainability and energy efficiency, and provides recommendations on how these materials can be more widely adopted and applied in future projects.

Keywords: Photoluminescent materials, innovative solutions, sustainable design, energy efficiency, eco-friendly illumination

DOI: 10.7176/JEES/14-6-04
Publication date: December 30th 2024

1. Introduction

Climate change is one of the biggest challenges of the 21st century. It is directly linked to the rapid urbanization and the resulting increasing ecological footprint. Climate change creates many negative environmental impacts, especially increased energy consumption and greenhouse gas emissions (Fabiani *et al.,* 2021; Chiatti *et al.,* 2022). In order to cope with these problems, it has become necessary to explore various active and passive measures optimized through energy sources that are based on renewable solutions aimed at reducing energy consumption and greenhouse gas emissions (Fabiani *et al.,* 2021; Chiatti *et al.,* 2021). In this respect, it can be concluded that proper selection of materials is of high importance especially for containing the level of energy consumption in structures and outdoors (Chiatti *et al.,* 2021).

Many municipalities have begun exploring smart city applications for public lighting. Among these innovative approaches are methods that supplement or replace artificial street lighting with bioluminescent transgenic plants and marine bacteria (Martínez *et al.,* 2023) (Figure 1). These applications present promising alternatives to meet the growing demand for sustainable and energy-efficient lighting solutions. However, among passive strategies, the use of cooling materials with high solar reflectance (SR) and thermal emissivity (ε) in cities stands out. These materials help keep urban and building surfaces cooler by reflecting and re-emitting incoming radiation, thereby reducing the urban heat island effect (Santamouris & Yun, 2020; Fabiani *et al.,* 2021; Chiatti *et al.,* 2021; Chiatti *et al.,* 2022). Materials used on building exteriors or urban pavements play a key role in the thermal energy balance of urban surfaces and local microclimates. A common characteristic among cooling materials is their high reflectance values, which help passively reduce surface and air temperatures by rejecting some of the incoming solar radiation. In this context, the application of photoluminescent elements to traditional building materials further enhances their cooling potential by actively releasing stored energy as visible light (Chiatti *et al.,* 2021; Chiatti *et al.,* 2022). These materials contribute to increasing energy efficiency and reducing the overall energy costs of buildings and infrastructure (Fabiani *et al.,* 2022; Chiatti *et al.,* 2023). Light space consumption accounts for more than half of the electricity consumption in cities (Sadeghian *et al.,* 2021) thus

innovative lighting solutions have also become an important area of research. In this context, the use of photoluminescent materials comes to the fore as a remarkable alternative (Chiatti *et al.,* 2022).

Figure 1. Examples of bioluminescence (Rogers, 2024)

The ability of materials to absorb light and later re-emit it at a different wavelength has made it possible to see photoluminescent materials as energy savers as well as materials that can be used for aesthetic enhancements (Garshasbi *et al.,* 2021). When exposed to light, these materials absorb energy and later re-emit it as visible light in the dark. This usually happens in two categories – the first one is fluorescent, which releases light as soon as it is absorbed while the second one called phosphorescent releases energy at a much slower rate thus allowing the material to remain luminous in the dark for hours. Fluorescent materials are designed in such a manner that they stop glowing when the source is removed and therefore are common when short term lighting effects are needed. Fluorescent materials that are pigments or coatings that glow for an extended period of time without a source that are used for safety sigs, road markings and emergency lighting systems (Shinde *et al.,* 2012; Sharma & Bairagi, 2018). The length of time for which light is emitted known as photoluminescence "lifetime" that can be days and in some cases weeks (Rosso *et al.,* 2019). In this regard, they are very appealing, especially in sustainable planning, architecture and construction projects, as energy saving devices (Shinde *et al.,* 2012). Photoluminescent compounds also have an importance in some of the applications such as replacing the currently with some new lighting devices (Chiatti *et al.,* 2022).

In recent years, there has been a rise in studies focused on integrating photoluminescent pigments with decorative concrete mixtures. These pigments serve as additive components when combined with materials like plastic, metal, or ceramics to enhance the aesthetic value of architectural features in urban infrastructure (Mateo Sanguino *et al.,* 2024). They provide an extra glow at night while maintaining the traditional performance characteristics of concrete. However, there is a lack of comprehensive research on using photoluminescent pigments in various building materials. Current applications reveal several significant drawbacks. For instance, existing techniques only enable the top decorative layer to glow, which can adversely affect the physical and mechanical properties of the material (Suleymanova *et al.,* 2020).

Typically, photoluminescent material applications are included as part of a project. Using these materials brings multiple benefits in aesthetics, safety, and functionality, especially in fields like landscape architecture and civil engineering. This study explores the advantages of this innovative material, highlighting its contributions to aesthetics, safety, and functionality through practical examples. It emphasizes the potential for innovative solutions, sustainability, and energy efficiency. Finally, suggestions are proposed for how this material can be more widely adopted and implemented in future research.

2. Material and Method

The material of the study consists of all kinds of national and international visual and written literature related to the topic and selected examples.

The method of the study consists of four stages:

i. Definitions about photoluminescent materials have been made;

ii. The use of photoluminescent materials, particularly in the fields of landscape architecture and civil engineering, has been examined, detailing the benefits offered by this material in terms of aesthetics,

safety, and functionality through implemented examples;

iii. The importance of these materials in terms of innovative solutions, sustainability, and energy efficiency, as well as their contributions, have been revealed;

iv. Suggestions have been developed on how this material could be adopted and applied more widely in future projects.

3. Benefits of Photoluminescent Materials

The main benefits offered by photoluminescent materials in terms of aesthetics, safety and functionality could be summarized as follows.

3.1. Aesthetic Benefits

Photoluminescent materials increase visibility at night and provide an aesthetic contribution to spaces with a natural glow effect. These materials, which are used in parks, walking paths, garden design and other open spaces, also provide design details at night. A path made of photoluminescent stones that glow in the dark or decorative objects and ornaments made of concrete materials containing photoluminescent materials increase environmental aesthetics and provide visual richness to the space where they are located (Suleymanova *et al.,* 2020) (Figure 2, 3). Impressive visuals that glow in water at night can be created to create an aesthetic effect on water features and pool edges (Stonecast, 2024) (Figure 4).

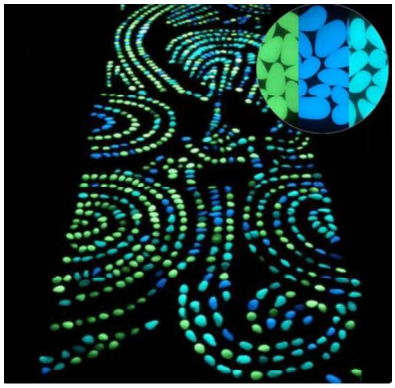


Figure 2. Concrete photoluminescent driveway with pebble application (Global Sources, 2024)

Figure 3. Decorative structures containing photoluminescent (Water X Scapes, 2024)

Figure 4. Photoluminescent water feature example (Stonecast, 2024)

As an alternative to traditional lighting elements, photoluminescent materials offer innovative lighting solutions. They can be used as both a natural and sustainable light source in walking paths, vehicle paths, bicycle paths, outdoor activity areas, etc. (Figure 5, 6). These materials create aesthetically striking elements while saving energy. They absorb light during the day and illuminate themselves at night or in low light conditions, allowing the roads to shine. Thus, it is thought that road safety will be improved by making streets, sidewalks, roads and/or crossings more visible (Martínez *et al.,* 2023). In addition, it will increase the safety of public areas such as parks (Suleymanova *et al.,* 2020).

Photoluminescent materials absorb photons from sources such as sunlight or vehicle headlights, and then emit light for periods ranging from a few nanoseconds to a few hours, making road signs more visible and can also increase road traffic and pedestrian safety (Bonneel *et al.,* 2023). Accidents are a significant road safety problem. Road signs using photoluminescent materials are an important application to improve drivers' perception of pedestrians, reduce fatalities and injury severity (Mateo Sanguino *et al.,* 2024). In this context, a white paint mixed with photoluminescent material that turns fluorescent light blue during the night can be used (Rosso *et al.,* 2019).

Figure 5. Photoluminescent marking on bicycle path (Bonneel *et al.,* 2023)

Figure 6. Concrete with photoluminescent (Olsztynska, 2017)

Extra bright pebble-shaped photoluminescent stones differentiate in the dark to give yellowish green, bluish green light, etc. Since the material is suitable for all kinds of processing or polishing, it can be applied both by

embedding the stones in different road surfaces (asphalt or pavement) and by mixing them with other decorative elements or natural covering materials (mulch, pebbles, etc.) (Figure 7). Exposing them to any natural or artificial light source for at least a few minutes provides a luminous effect of 3 - 10 hours, depending on the brightness of the night and the size of the stones (Herlig, 2024).

Figure 7. Extra bright pebble shaped photoluminescent stones (Herlig, 2024).

Luminescent glass grits are available in green and blue tones. Its most frequent use is integrating into pavements, decorative elements or natural coatings such as mulch, gravel, etc. The material, mixed with luminescent grit adhesives and rock mass substrate (gravel or grit), is not only durable but also serves as an aesthetic design element during evening hours (Figure 8). This material is widely used in concrete slabs requiring a decorative function, as well as in paving stones, cement tiles, etc. (Herlig, 2024).

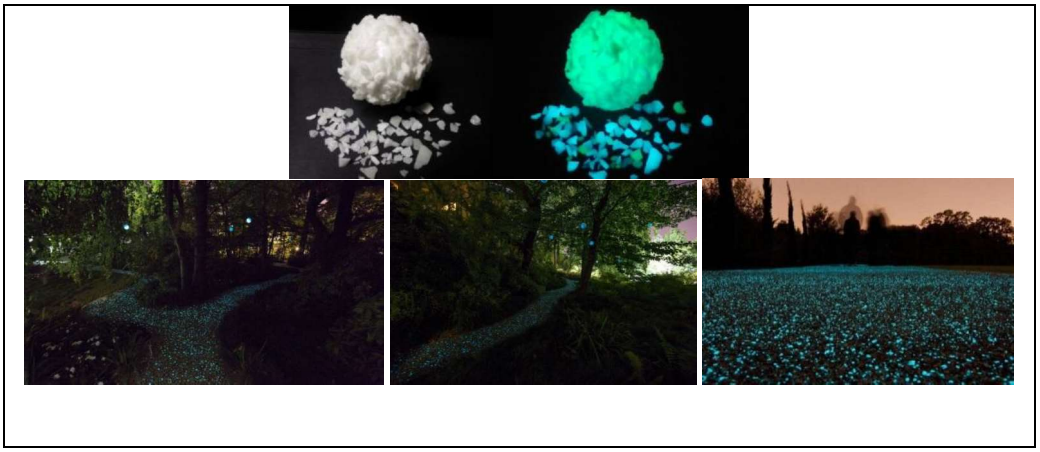


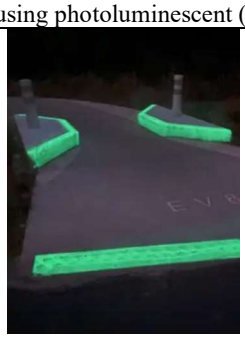
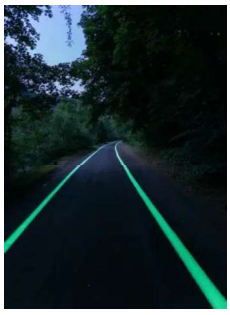
Figure 8. Luminescent grit glass (Herlig, 2024).

3.2. Safety Benefits

The use of photoluminescent materials in areas such as road signs, pedestrian crossings, bicycle paths, parking lots, etc. helps prevent accidents and injuries to pedestrians and drivers (bicycles, motorcycles, vehicles) by increasing night visibility. Road markings increase driver safety, especially in areas with low night visibility. These materials facilitate drivers' navigation by being used on the edges of roads or on curves and prevent accidents (Martínez *et al.,* 2023; Bonneel *et al.,* 2023). Photoluminescent coatings and paints are used on building facades, bridges, tunnels or other civil engineering structural elements, increasing the aesthetic value in both landscape and construction projects, and providing road safety (Figure 9; Table 1).

Figure 9. Photoluminescent road marking (Luminokrom, 2024a)

Table 1. Examples of safety benefits of using photoluminescent (Luminokrom, 2024b)

Application	**:**			
Safety benefit	**:**	Photoluminescent usage to clearify unexpected obstacles.	Photoluminescent usage to clearify caution.	Photoluminescent usage as direction signage.
Application	**:**			
Safety benefit	**:**	Photoluminescent marking for safe navigation on bridges or footbridges.	Photoluminescent marking on riverbank that must not be crossed.	Photoluminescent marking to clearify virages.

In particular, the addition of photoluminescent properties to concrete and coating materials used in closed areas such as tunnels, indoor parking lots, etc. can provide better illumination of areas and increase road safety (Figure 10). Lighting in tunnels plays an important role in ensuring traffic safety, reducing accident losses, implementing effective road guidance and increasing traffic safety (Zhao *et al.,* 2021) (Figure 11).

Figure 10. Luminous tunnel lighting examples (Zhao *et al.,* 2021)

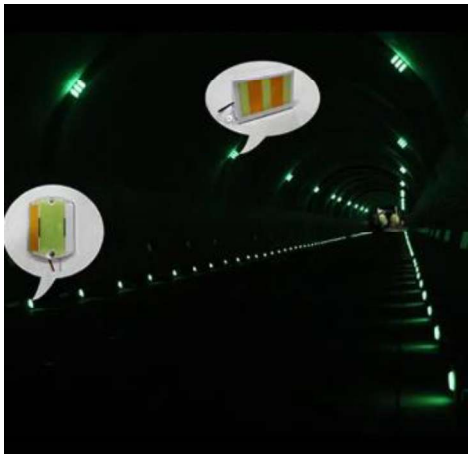


Figure 11. Luminous tunnel sign example (Minhui Luminous, 2024)

Photoluminescent materials can also be used as warning signs or signs indicating evacuation routes and exits in emergency situations. They can be used in places such as emergency exit signs of buildings or open spaces, guide signs, traffic signs on vehicle roads, direction signs, etc. (Figure 12-14). These materials ensure that signs remain visible in the absence of lighting, low light conditions, or in the event of a power outage, and increase safety in emergency situations. (Sharma & Bairagi, 2018; Zhao *et al.,* 2021; Bren Inc., 2024). In addition, photoluminescent materials are used in the design and implementation of road signs and road markings, and in ensuring visibility during the day and at night (Martínez *et al.,* 2023).

Figure 12. Example of photoluminescent warning signs used in public spaces (Toptend, 2024)

Figure 13. Photoluminescent film safety signs applied inside buildings (Bren Inc., 2024)

Figure 14. Photoluminescent traffic sign example (Jiangsu Entai Lighting Group, 2024)

Photoluminescent materials can also be used in children's playgrounds to increase visibility and ensure safety at night. Photoluminescent lines or markings placed around playground equipment such as slides, swings, trampolines, etc. in a children's playground allow children to move safely in the playground and increase the visibility of the park at night. For example, the first "glow in the dark" playground in Texas, which was opened in 2023, has interactive and bright areas that provide fun both during the day and at night. In this park called "JOYA", the 18,000 m2 main playground area includes elements such as climbing, swings, obstacle courses, and zip lines. In addition, there is another 7,000 m2 bright (illuminated) area for children aged 2-5 (Figure 15). The project offers a new approach to children's playgrounds in terms of energy saving and fun (Garcia, 2023).

Figure 15. Glowing playground example - JOYA (Melz, 2024)

In another study, a children's playground was designed using photoluminescent paint (Figure 16). Due to its attractive lighting and durable structure, a playground open to people of all ages, reviving active play, curiosity and discovery, was created (Yeadon, 2013).

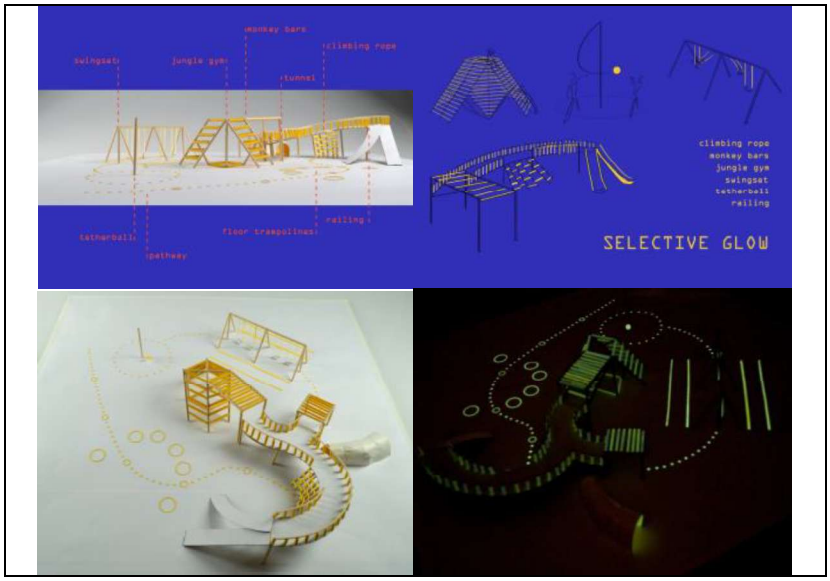


Figure 16. An example of a children's playground using photoluminescent paint (Yeadon, 2013)

As global warming progresses at an alarming rate, the demand for passive radiative cooling solutions, that can capable of cooling objects without consuming energy, has seen a significant rise (Rosso *et al.,* 2019; Chiatti *et al.,* 2021; Garshasbi *et al.,* 2021; Chiatti *et al.,* 2022; Chiatti *et al.,* 2023). The studies working with photoluminescent paint state that the urban heat island effect can be reduced with the properties of the paint. The smart photoluminescent paint developed in the laboratory is formed by combining a solvent and photoluminescent pigments. The pigment is white when " discharged", but when "charged" with energy, it appears blue when light is emitted from the material itself. The material is cold due to high solar reflectance and can be considered as a "storage of energy for lighting" (LES), similar to the concept of thermal energy storage (TES) due to intrinsic photoluminescence, similar to phase change materials (PCM) with thermal energy (Rosso *et al.,* 2019; Fabiani *et al.,* 2021). A large part of the incoming solar radiation is reflected due to high solar

reflectance. Fluorescent materials cause additional radiative losses due to fluorescence emission at certain wavelengths. Thus, the entry of high temperatures into the building is prevented and the energy demand for cooling is reduced. Another advantage is the reduction of electricity used for lighting. Since the material is photoluminescent, it emits light for a certain period of time after absorbing energy, thus requiring less electricity in the environment to provide illumination (Rosso *et al.,* 2019; Santamouris & Yun, 2020; Fabiani *et al.,* 2021; Chiatti *et al.,* 2021).

3.3. Functionality Benefits

Photoluminescent materials offer an innovative and sustainable option for lighting public spaces. Since they work without the need for electrical energy, they greatly reduce energy consumption. In this way, they contribute to both economic and environmental sustainability. These materials are indispensable for environmentally friendly designs in urban areas and infrastructure. They are long-lasting and require minimum maintenance. In addition, their integration into existing infrastructures does not require additional costs, which makes them cost-effective for urban planners. Photoluminescent materials help cities reduce their carbon footprint and offer an advanced alternative to conventional lighting systems. A report by UL Solutions highlights that these materials improve energy efficiency and reduce carbon emissions in public spaces by reducing energy use. They are also increasingly favoured in smart city projects where it is critical to improve public safety while saving energy. Their ability to be used both indoors and outdoors minimises environmental impacts while increasing energy efficiency (UL Solutions, 2022). In the study conducted by Martinez et al. (2023), which contributes similarly to the functional benefits mentioned, it is stated that these materials can be used in lighting solutions, do not require environmentally harmful chemicals and provide significant contributions to sustainability goals with low maintenance costs. From another perspective, it has been proven in the literature that the urban heat island effect seen in urban areas can be reduced thanks to the properties of photoluminescent materials (Santamouris & Yun, 2020; Sadeghian *et al.,* 2021). Coatings and materials with low surface temperatures have been developed in order to reduce the negative effects of overheating of urban areas on the environment, energy and health. While traditionally used light-colored materials provide a solution to this problem, in recent years, innovative materials with high reflective properties, including photoluminescent materials, have been applied in large urban projects. These materials have shown significant success in reducing surface temperatures and heat released into the atmosphere. Photonic materials and structures offer promising and effective technological priorities. However, challenges such as long-term durability and cost-effectiveness of the materials still need to be solved. While research based on technologies such as photonic structures, nanofluorescent materials and thermochromic dyes offer potential solutions in these areas, future studies should focus on improving the thermal performance of these materials, reducing their costs and industrial scaling (Santamouris & Yun, 2020).

4. Importance and Contributions of Photoluminescent Materials

Photoluminescent materials can be used in a wide variety of areas, especially in landscape architecture and civil engineering projects. Landscape architects prefer these materials for aesthetic and functional purposes in outdoor spaces, while civil engineers generally prefer them for structural and security reasons. Photoluminescent materials, which allow for collaboration and innovative solutions in joint projects thanks to their wide range of applications, are ideal for many projects because of their ability to meet aesthetic, security and functional demands.

In general, the importance of photoluminescent materials and the contributions and benefits they offer can be summarized as follows:

- Photoluminescent materials can significantly reduce energy consumption in urban environments by providing alternative lighting solutions that do not rely on electricity.
- The integration of luminescent materials in building facades and pavements can contribute to lower overall lighting costs, especially in areas with limited access to the electrical grid
- Luminescent materials with high solar reflectance can effectively mitigate the urban heat island effect by reflecting a larger portion of solar radiation back into the atmosphere
- Implementing photoluminescent coatings on building surfaces can not only enhance nighttime visibility but also reduce the thermal load during the day.
- Recent studies have shown that luminescent materials can be applied in various parts of the built

environment, including road markings, building facades, and pedestrian pathways, to improve safety and aesthetics.

- Innovative applications of luminescent technologies are being explored to create self-illuminating surfaces in public spaces, reducing the need for conventional street lighting.
- Luminescent materials contribute to sustainability goals by reducing the dependency on fossil fuel-based energy sources for lighting.
- These materials provide both energy efficiency and reduce light pollution. They make urban areas more sustainable and environmentally friendly.
- However, despite all these benefits, there are challenges in integrating photoluminescent materials into existing urban infrastructure, especially in terms of cost and public acceptance.

5. Conclusion and Suggestions

As cities grow rapidly, energy consumption and carbon emissions increase significantly. This exacerbates global climate change and highlights the urgency of meeting the growing energy needs of cities in sustainable ways. Recent research focuses on increasing overall efficiency while reducing energy use and emissions in the built environment (Rosso *et al.,* 2019). In this context, photoluminescent materials offer an eco-friendly option. They reduce energy consumption and carbon footprint by reducing the need for traditional electric lighting systems. In addition to their aesthetic and functional benefits, these materials are also valuable in terms of environmental sustainability.

For these reasons, more widespread use and application of photoluminescent materials is crucial to support environmental sustainability and integrate them into smart city infrastructures. In order to promote the future development and wider use of this innovative material, the following recommendations are presented:

- Extensive research is needed to assess the long-term performance and durability of photoluminescent materials. Understanding their longevity and resilience in various applications will boost confidence in their reliability and facilitate their widespread implementation. Studies have indicated that luminescent paints applied to light-colored surfaces achieve higher brightness levels compared to those obtained with bituminous mixtures and mortars, while also reducing the amount of material needed. Comparing the performance of photoluminescent materials in different environments and projects could help to redefine their effectiveness. As Chiatti *et al.* (2022) pointed out, their behavior on various surfaces and mixtures needs closer examination. Bonneel et al. (2023) also noted that, since sustainable and high-performance photoluminescent road markings are still relatively new, more research is necessary to fully understand and evaluate these products.
- It's equally important to explore how photoluminescent materials can be integrated with smart cities and interactive design solutions. Studies should focus on how these materials can be combined with smart lighting systems, sensors, and other technologies to enhance their performance. For instance, studying the wider use of photoluminescent pedestrian crossings and how they could fit into other smart city initiatives would be valuable (Mateo Sanguino *et al.,* 2024). Additionally, as Fabiani *et al.* (2021) suggested, optimizing the interaction between the material and light is crucial. This includes examining the long-term durability of these dynamic materials and assessing the economic feasibility of using them on a large scale in smart and sustainable urban environments. Because the adoption of luminescent technologies in public infrastructures can support broader sustainability initiatives and promote green urban development. For example, Osaka University and Nara Institute of Science and Technology in Japan are conducting research on "luminescent plants" to develop energy-efficient lighting solutions with the aim of reducing carbon dioxide emissions (Figure 17). These plants are being developed using bioluminescent bacteria and luminescent jellyfish genes. Although the light intensity is still low, it is aimed to provide lighting in cities without using electricity in the future. They are also working on ways to prevent the plant from growing naturally, such as modifying its genes to prevent it from producing flowers and seeds. So, it could be more suitable as roadside trees. This study, which focuses especially on poplar trees, promises hope for eco-friendly lighting solutions. (Groovy, 2021).

Figure 17. Glowing poplar trees (Groovy, 2021)

- Studies in the literature do not address their use in public spaces. However, the methodologies and findings of the studies provide implications on how photoluminescent materials can be adapted to improve visibility in public spaces such as children's playgrounds and reduce accident risks in the dark. More studies clearly focusing on uses in public spaces are needed.
- More research should focus on optimizing the performance of luminescent materials for urban heat island reduction while minimizing possible disadvantages. The potential for application of such paint in different locations such as cities, parks, historical sites or mountain houses should be investigated in more depth (Rosso *et al.,* 2019). The integration of photoluminescent materials with different building materials should be explored to help reduce the urban heat island effect. It's particularly important to study how these materials respond to various weather conditions, wear and tear, and chemical exposure.
- Collaboration among urban planners, civil engineers, landscape architects, and local authorities is crucial for creating a holistic approach that seamlessly incorporates photoluminescent systems into existing infrastructure. This would not only enhance road safety but also improve the overall effectiveness of urban designs (Mateo Sanguino *et al.,* 2024).
- Local governments should prioritize including luminescent materials in urban development plans to achieve energy efficiency and sustainability goals.
- As noted by Bonneel *et al.* (2023), further research is needed to understand user satisfaction, perceptions, and feedback regarding these materials. Understanding user satisfaction will be essential for evaluating how these spaces are used and for offering recommendations to boost their adoption.

As a result, photoluminescent materials have an important place in terms of both aesthetics and safety. They also reduce energy consumption and minimise environmental impacts in cities. The fact that they emit light without requiring electricity increases energy efficiency and makes them an indispensable part of sustainable urban planning. Their potential to provide solutions to increasing energy demands and global challenges such as climate change represents a great opportunity, especially in densely urbanised areas. They improve night vision, ensuring the safety of both pedestrians and drivers. On the other hand, more research and applications are needed for more widespread use of these materials in urban design. Long-term studies will be critical for the integration of these materials into sustainable and smart city systems. Future research examining the contribution of these materials to smart city solutions will increase both economic and environmental sustainability.

References

Bren Inc. (2024). PH12 Photoluminescent Film. [Online] Available: https://www.breninc.com/product/pha10-photoluminescent-film/ (August 12, 2024)

Bonneel, L., Geisler, F., Létard, J.F. & Villa, C. (2023). LuminoKrom®: Photoluminescent road marking for safe mobility at night. *Transportation Research Procedia*, 72, 3754–3761. https://doi.org/10.1016/j.trpro.2023.11.514

Chiatti, C., Fabiani, C., Bondi, R., Zampini, G., Latterini, L. & Pisello, A.L. (2023). Controlled combination of phosphorescent and fluorescent materials to exploit energy-saving potential in the built environment. *Energy*, 275, 127333. https://doi.org/10.1016/j.energy.2023.127333

Chiatti, C., Fabiani, C., Cotana, F. & Pisello, A.L. (2021). Exploring the potential of photoluminescence for urban passive cooling and lighting applications: A new approach towards materials' optimization. *Energy*, 231, 120815. https://doi.org/10.1016/j.energy.2021.120815

Chiatti, C., Kousis, I., Fabiani, C. & Pisello, A.L. (2022). Luminescence for the built environment: from lighting to urban heat island mitigation purposes. In; Global Urban Heat Island Mitigation, Chapter 3, 47-69. https://doi.org/10.1016/B978-0-323-85539-6.00005-6

Fabiani, C., Chiatti, C. & Pisello, A.L. (2021). Development of photoluminescent composites for energy efficiency in smart outdoor lighting applications: An experimental and numerical investigation. *Renewable Energy*, 172, 1-15. https://doi.org/10.1016/j.renene.2021.02.071

Fabiani, C., Gambucci, M., Chiatti, C., Zampini, G., Latterini, L. & Pisello, A.L. (2022). Towards field implementation of photoluminescence in the built environment for passive cooling and lighting energy efficiency. *Applied Energy*, 324, 119687. https://doi.org/10.1016/j.apenergy.2022.119687

Garshasbi, S., Huang, S., Valenta, J. & Santamouris, M. (2021). Enhancing the cooling potential of photoluminescent materials through evaluation of thermal and transmission loss mechanisms. *Scientific Reports*, 11, 14725. https://doi.org/10.1038/s41598-021-94354-7

Garcia, A. (2023). Nation's first glow-in-the-dark playground is coming to North Texas. [Online] Available: https://www.chron.com/news/houston-texas/article/texas-glow-in-the-dark-playground-18177160.php (August 12, 2024)

Global Sourcaes (2024). Night Luminous Pebbles Concrete Photoluminescent Driveway Glow Stone. [Online] Available: https://www.globalsources.com/product/courtyard-luminous-decoration_1206289143f.htm (August 12, 2024)

Groovy, S. (2021). Japanese Universities Create Glowing Tree For Non-Electric Lights. [Online] Available: https://www.groovyjapan.com/en/glow-plant/ (August 12, 2024)

Herlig (2024). About Luminescent Materials. [Online] Available: http://www.herlig.eu/luminescent-materials/ (August 12, 2024)

Jiangsu Entai Lighting Group (2024). Manufactory Made Fluorescent and Noctilucence Photoluminescent Traffic Signs Street Signs. [Online] Available: https://jsetzm.en.made-in-china.com/product/qZAxCQRygLkG/China-Manufactory-Made-Fluorescent-and-Noctilucence-Photoluminescent-Traffic-Signs-Street-Signs.html (August 12, 2024)

Luminokrom (2024a). The Luminescent Road Marking of Trafficked Areas. [Online] Available: https://www.luminokrom.com/en/products/traffic-area-light-marking/ (August 12, 2024)

Luminokrom (2024b). Luminokrom Accompanies You On Your Bike Trip. [Online] Available: https://www.luminokrom.com/en/luminokrom-accompanies-you-on-your-bike-trip/ (August 12, 2024)

Martínez, A.H., López-Montero, T., Miró, R. & Puig, R. (2023). Photoluminescent Applications for Urban Pavements. *Sustainability*, 15, 15078. https://doi.org/10.3390/su152015078

Mateo Sanguino, T.d.J., Redondo González, M.J., Davila Martin, J.M. & Lozano Domínguez, J.M. (2024). Enhanced Road Safety with Photoluminescent Pedestrian Crossings in Urban Contexts. *Infrastructures*, 9, 60. https://doi.org/10.3390/infrastructures9030060

Melz (2024). The First Ever Glow-In-The-Dark Playground In Texas Opens This Weekend. [Online] Available: https://klaq.com/ixp/186/p/the-first-ever-glow-in-the-dark-playground-in-texas-opens-this-weekend/ (August 12, 2024)

Minhui Luminous (2024). Factory Outlets for Glow In The Dark Road Marking Powder - Luminous Tunnel Sign. [Online] Available: https://www.mphotoluminescent.com/factory-outlets-for-glow-in-the-dark-road-marking-powder-luminous-tunnel-sign-minhui-luminous.html (August 12, 2024)

Olsztynska, G. (2017). This Glow-In-The-Dark Bike Path is Powered By The Sun. [Online] Available: https://www.playcore.com/news/this-glow-in-the-dark-bike-path-is-powered-by-the-sun (August 12, 2024)

Rogers, D. (2024). Bioluminescence Photography Tips. [Online] Available: https://www.canon.com.au/get-inspired/bioluminescence-photography-tips (August 12, 2024)

Rosso, F., Fabiani, C., Chiatti, C. & Pisello, A.L. (2019). Cool, photoluminescent paints towards energy consumption reductions in the built environment. *Journal of Physics: Conference Series*, 1343, 012198.

https://doi.org/10.1088/1742-6596/1343/1/012198

Sadeghian, O., Moradzadeh, A., Mohammadi-Ivatloo, B., Abapour, M., Anvari-Moghaddam, A., Lim, J.S. & Marquez, F.P.G. (2021). A comprehensive review on energy saving options and saving potential in low voltage electricity distribution networks: Building and public lighting. *Sustainable Cities and Society*, 72, 103064. https://doi.org/10.1016/j.scs.2021.103064

Santamouris, M. & Yun, G.Y. (2020). Recent development and research priorities on cool and super cool materials to mitigate urban heat island. *Renewable Energy*, 161, 792-807. https://doi.org/10.1016/j.renene.2020.07.109

Sharma, R. & Bairagi, N. (2018). The Role of Photoluminescent Pigments in Textiles. *Trends in Textile Engineering & Fashion Technology,* 2(2), 164-167. https://doi.org/10.31031/TTEFT.2018.02.000533

Shinde, K.N., Dhoble, S.J., Swart, H.C. & Park, K. (2012). Basic Mechanisms of Photoluminescence. In: Phosphate Phosphors for Solid-State Lighting. Springer Series in Materials Science, 174. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-34312-4_2

Stonecast (2024). Photoluminescent Concrete. [Online] Available: https://stonecast.co.za/photoluminescent-concrete/ (August 12, 2024)

Suleymanova, L., Maliukova, M. & Koryakina, A. (2020). Architectural and decorative concrete with photoluminescent pigment. IOP Conf. Series: Materials Science and Engineering, 896, 012025. https://doi.org/10.1088/1757-899X/896/1/012025

Toptend (2024). Glow in The Dark Luminous Film H9200. [Online] Available: https://toptend.com/product/photoluminescent-glow-in-the-dark-vinyl-film/ (August 12, 2024)

UL Solutions (2022). Illuminating a Brighter, Healthier and More Sustainable Future for the Lighting Solutions Industry. [Online] Available: https://www.ul.com/news/sustainability-solutions-lighting-industry (August 12, 2024)

Water X Scapes (2024). Pondless Water Feature Photo Gallery. [Online] Available: https://waterxscapes.com/pondless-water-feature-photo-gallery/ (August 12, 2024)

Yeadon, P. (2013). Luz Playground. [Online] Available: https://www.behance.net/gallery/13347629/Lux-playground (August 12, 2024)

Zhao, X., Zhang, C., Ju, Y., Li, J., Bian, Y. & Ma, J. (2021). Evaluation of tunnel retro-reflective arch in an extra-long tunnel based on the matter-element extension method. *Accident Analysis and Prevention*, 150, 105913. https://doi.org/10.1016/j.aap.2020.105913