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Sensory Materials for the Sustainable Revitalization of Public Spaces: Development and Evaluation of Photoluminescent and Aromatic Bricks

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Sensory Materials for the Sustainable Revitalization of Public Spaces: Development and Evaluation of Photoluminescent and Aromatic Bricks

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Abstract

The quality and functionality of urban public spaces are often limited by inadequate nighttime lighting, low sensory comfort, and inefficient construction waste management, reducing usability and perceived safety. This study aims to develop and evaluate sensory materials for the sustainable revitalization of public spaces through the design of photoluminescent and aromatic bricks using recycled materials. A mixed-method experimental approach was adopted, including prototype fabrication and performance assessment through illuminance, luminance, volatile compound release, and physical property tests. The results indicate that the developed bricks achieve illuminance levels of approximately 2 lux under real conditions, within the recommended range for low-activity pedestrian areas, and exhibit moderate and sustained aromatic release with functional performance up to 0.90 m. In addition, the materials show adequate physical stability, mechanical resistance, and controlled water absorption. These findings suggest that the proposed materials can contribute to improving nighttime visibility and sensory perception in public spaces. This study proposes an integrated approach combining material innovation and urban design, supporting the use of passive multisensory strategies for sustainable public space revitalization.

Keywords: multisensory materials; public space design; sustainable urban design; photoluminescence; aromatic compounds; urban revitalization; recycled materials

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1. Introduction

The quality and functionality of urban public spaces play a fundamental role in social well-being, safety, and urban sustainability. However, in many cities—particularly in Latin America—these spaces are often affected by inadequate nighttime lighting, limited environmental comfort, and inefficient construction waste management, which reduce usability, accessibility, and users' perception of safety. In this context, insufficient urban lighting remains a critical issue associated with inefficient infrastructure and increased perceived insecurity during nighttime hours [1,2]. Globally, road traffic accidents account for approximately 1.19 million deaths annually, of which nearly 23% correspond to pedestrians, highlighting their vulnerability in poorly designed urban environments [3].

At the same time, the environmental impact [4] of construction and demolition waste has become increasingly relevant within sustainable urban development. It is estimated that approximately 2240 million tons of such waste are generated worldwide, with a significant proportion not being properly recycled [5,6]. Additionally, forestry residues, particularly from eucalyptus, represent an underutilized resource with potential for integration into construction materials [7]. In this context, the development of sustainable materials incorporating recycled components emerges as a key strategy to reduce environmental impact and promote circular economy principles.

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Recent studies have explored photoluminescent materials as an alternative to improve nighttime visibility in urban environments, particularly those based on strontium aluminate ($SrAl_2O_4$:Eu,Dy), due to their capacity for energy absorption and persistent light emission [8,9]. These materials have demonstrated potential for passive lighting applications in pavements and urban elements, contributing to reduced energy consumption [10–12]. In parallel, research on aromatic materials has focused on incorporating volatile compounds into porous matrices, enabling controlled scent release through essential oils and organic additives [13–15].

Despite these advances, existing studies have largely addressed luminescent and aromatic properties separately, with limited integration into a unified approach for urban design. Furthermore, while some studies emphasize technical performance (e.g., light emission efficiency or durability), others highlight user perception and sensory experience, revealing a lack of convergence between material performance and urban experiential quality. This fragmentation indicates a research gap in linking material innovation with multisensory urban design strategies.

In this context, this study proposes the development and evaluation of photoluminescent and aromatic bricks as sensory materials for the sustainable revitalization of public spaces. The research focuses on Melgar Park in Arequipa, Peru, where issues such as inadequate lighting, low user permanence, and limited spatial quality have been identified. A mixed-method experimental approach is employed to design and assess prototypes made from recycled materials in terms of luminous, aromatic, and physical performance under real conditions.

The results show that the developed materials achieve illuminance levels of approximately 2 lux, within recommended ranges for low-activity pedestrian environments, and provide sustained aromatic release at short and medium distances. These findings suggest that integrating luminous and olfactory properties into construction materials can enhance spatial perception, orientation, and nighttime usability. Therefore, this study contributes to bridging material science and urban design by proposing sensory materials as a strategy for sustainable and multisensory public space revitalization.

2. Materials and Methods

2.1. Research Approach

This study adopts a mixed-method experimental design aimed at developing and evaluating sensory materials for sustainable public space revitalization. The methodology integrates laboratory-based material development in situ performance assessment under real environmental conditions, enabling the analysis of luminous, aromatic, and physical properties in an applied urban context.

The research process was structured into six phases (Figure 1): (1) urban context analysis, (2) material design, (3) preparation of aromatic compounds, (4) incorporation of photoluminescent properties, (5) experimental evaluation, and (6) urban application.

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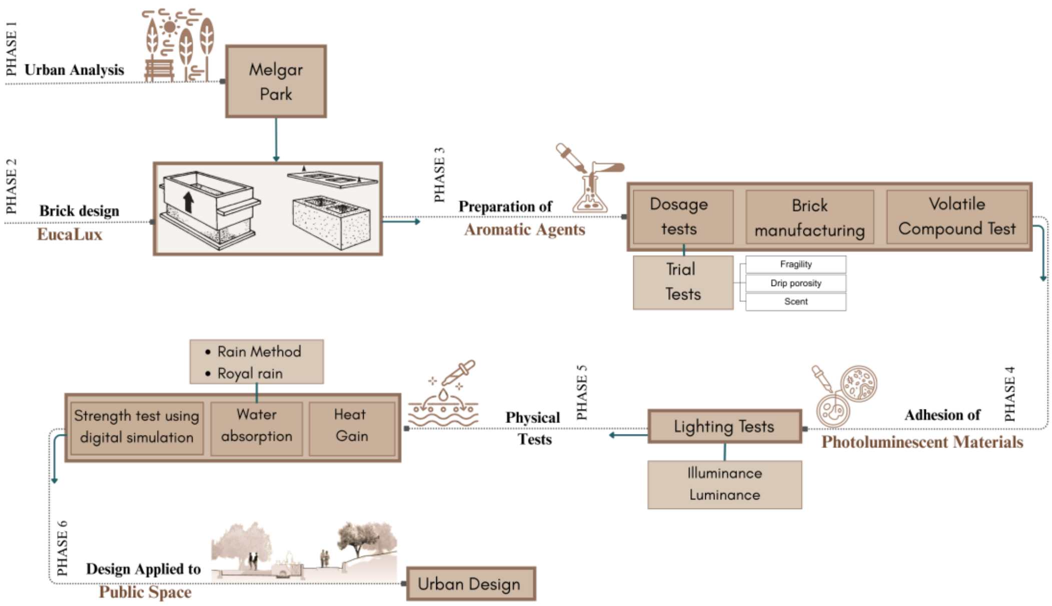

Figure 1. Methodological framework illustrating the sequential phases of material development and urban application

2.2. Study Area

The study was conducted in Melgar Park, located in the historic center of Arequipa, Peru. This public space is characterized by high pedestrian flow and urban connectivity but presents deficiencies in nighttime lighting, spatial quality, and user permanence, making it suitable for evaluating sustainable revitalization strategies (Figure 2).

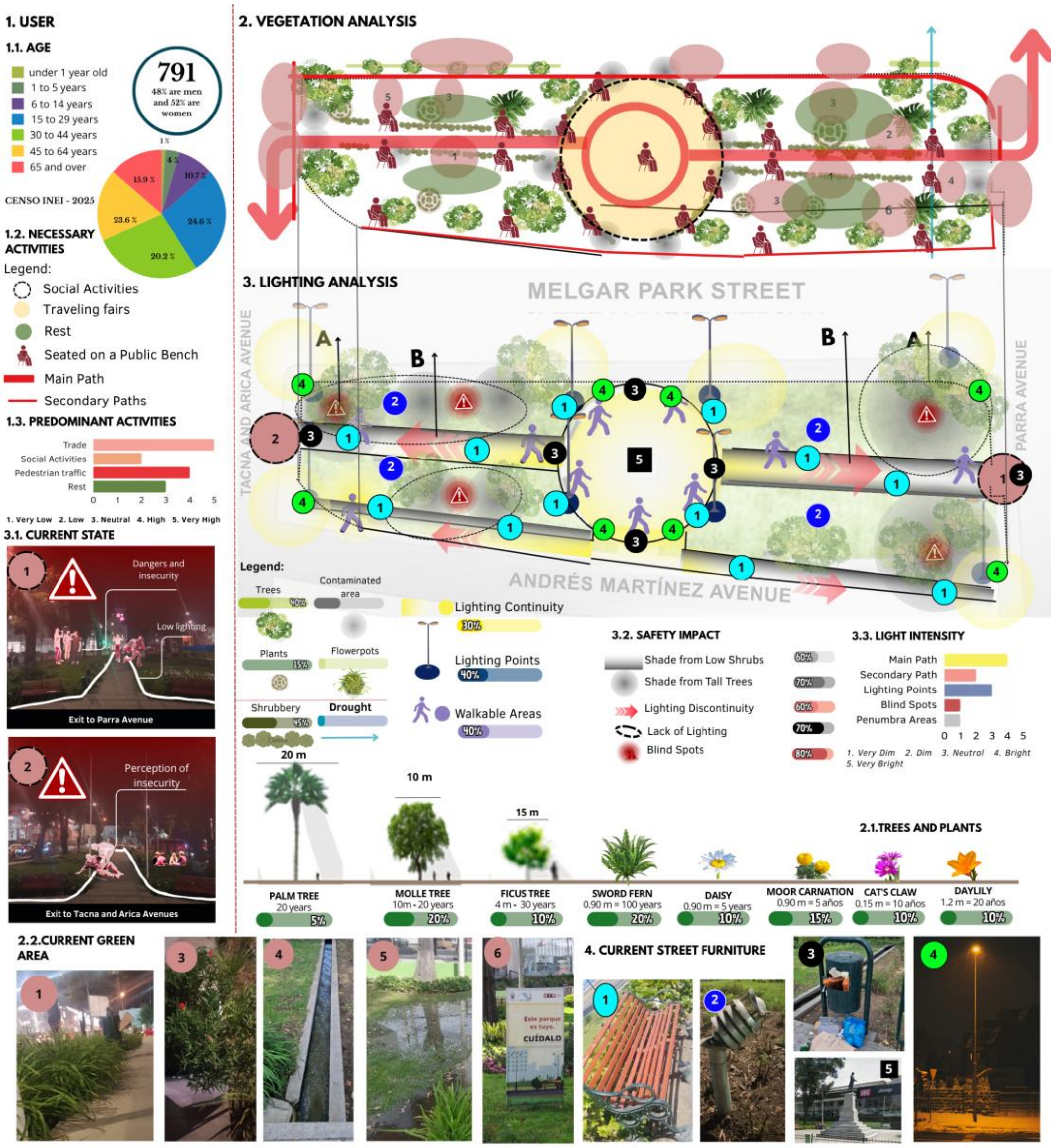

Figure 2. Study area characterization of Melgar Park, including spatial analysis and identified deficiencies in lighting and urban quality.

2.3. Material Design (EucaLux Brick)

A prototype EucaLux Brick (EucaLux-M12) was developed based on standard paving dimensions (20 × 10 × 4 cm). The material matrix consisted of locally sourced components, including clay, sillar, pozzolana, and lime, selected to promote sustainability using regional resources.

The EucaLux Brick geometry incorporates internal perforations to enhance drainage, ventilation, and integration of functional components. Two configurations were developed for experimental comparison (Figure 3).

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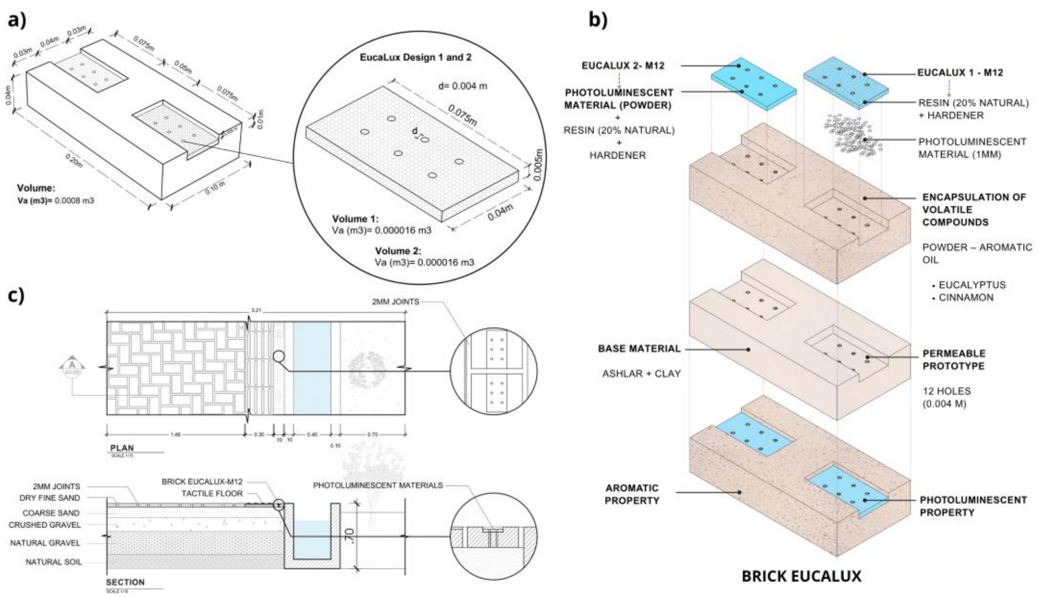

Figure 3. Design and technical configuration of the EucaLux brick: (a) geometric design, (b) technical diagram, and (c) construction detail.

2.4. Preparation of Aromatic Compounds

Aromatic compounds were prepared using eucalyptus and cinnamon essential oils through maceration processes in olive oil and ethanol (50% each) over 30 days under controlled dark conditions [16,17]. The extracts were filtered and mixed with plant powder, ethanol, water, and vinegar, followed by thermal agitation below 60 °C to stabilize volatile compounds [13].

The resulting mixture was incorporated into the base material using a controlled thermal process at 80 °C, followed by molding, drying (48 h), and kiln curing (6 h) to ensure structural stability and retention of aromatic properties (Table 1).

Table 1. Composition of EucaLux brick prototypes (M1–M12) used for experimental evaluation, indicating material proportions and functional components.

Sample	Clay (g)	Lime (g)	Cement (g)	Pozzolan (g)	Sillar (g)	Resin (mL)	Fiber (g)	Aroma (g)
M1	63.4	14	–	14	14	–	–	23.8
M2	63.4	14	–	14	14	8	–	23.8
M5	63.4	14	–	14	14	8	1.7	23.8
M12	23.8	7	53.9	14.3	14.3	8	3.4	33

2.5. Photoluminescent Integration

Photoluminescent properties were incorporated using strontium aluminate-based materials. Two application methods were tested:

(i) layered surface application using resin and photoluminescent aggregates, and

(ii) homogeneous incorporation of photoluminescent powder within the material matrix.

All samples were cured for 24 h under controlled conditions to ensure material stability [9,11].

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2.6. Experimental Evaluation

2.6.1. Aromatic Release Test

The release of volatile compounds was evaluated using the Odor Activity Value (OAV) method in accordance with ASTM E679-19 [18]. Five samples were arranged linearly and exposed to solar radiation for 5 h (08:00–13:00). Measurements were taken at distances of 0.30 m, 0.60 m, and 0.90 m (Figure 4).

Participants evaluated odor intensity under two conditions (standing and seated). All participants provided informed consent prior to the evaluation. The study did not involve vulnerable populations or invasive procedures.

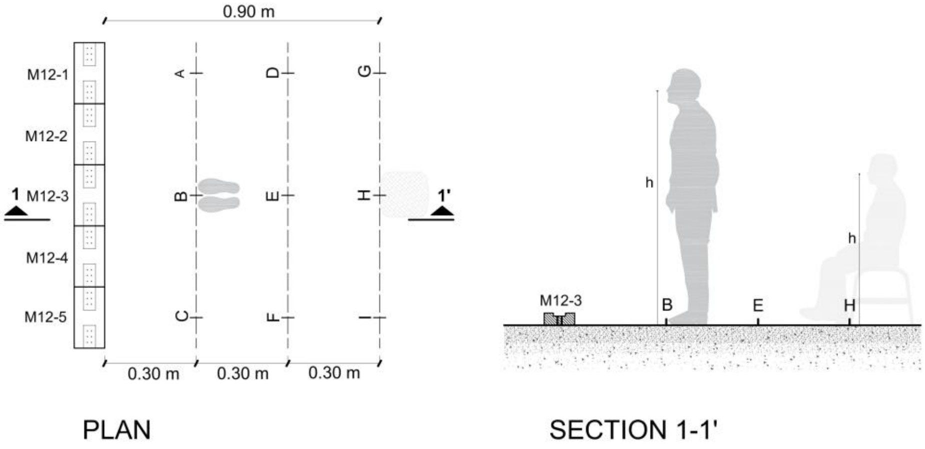

Figure 4. Experimental setup for Odor Activity Value (OAV) evaluation at different distances (0.30 m, 0.60 m, and 0.90 m).

2.6.2. Photometric Measurements

Illuminance was measured using a digital lux meter (Extech LT300) at hourly intervals between 19:00 and 04:00 under both real and controlled conditions (Figure 5). Measurements were compared with the Illuminating Engineering Society standard (IES G-1-16), which recommends 2–5 lux for low-activity pedestrian areas [19].

Luminance values were calculated from illuminance data using standard photometric relationships and expressed in cd/m², following NTP-ISO 3864-4:2016 [20].

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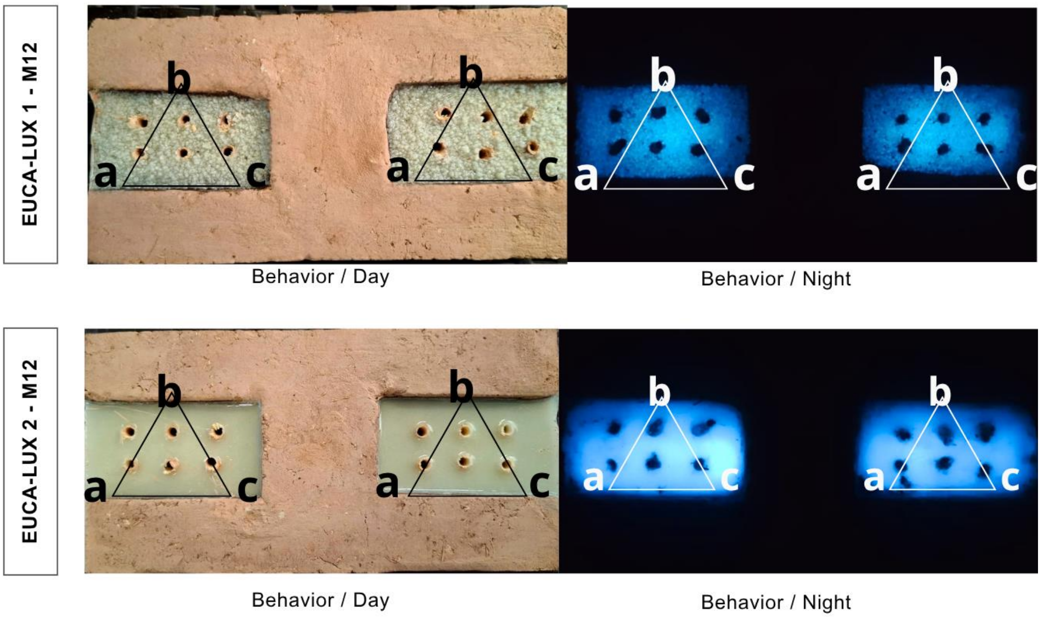

Figure 5. Experimental setup for illuminance measurement under real and controlled conditions.

2.6.3. Physical Properties

Water absorption was evaluated through immersion and real rainfall exposure tests, following NTP 399.613:2017 [21]. Thermal behavior was assessed using a thermal imaging camera, recording temperature variations throughout the day.

Compressive strength was analyzed through digital simulation (Autodesk Inventor 2021) under loads of 35 MPa, 70 MPa, and 105 MPa to assess structural performance.

2.7. Urban Application

The developed materials were applied in a design proposal for Melgar Park, integrating sensory pathways within pedestrian circulation systems. This phase allowed for the evaluation of the material's applicability in real urban conditions, considering accessibility, spatial organization, and sensory interaction.

3. Results

3.1. Release of Volatile Aromatic Compounds

The results of the volatile compound release test, evaluated using the Odor Activity Value (OAV) method, show variations in aromatic intensity as a function of distance and user position.

At 0.30 m, aromatic intensity is mainly concentrated at levels 2, 3, and 4 of the OAV scale, indicating a perceptible and relatively homogeneous emission. At this distance, slightly higher intensity values are observed in the seated position compared to the standing position (Figure 6).

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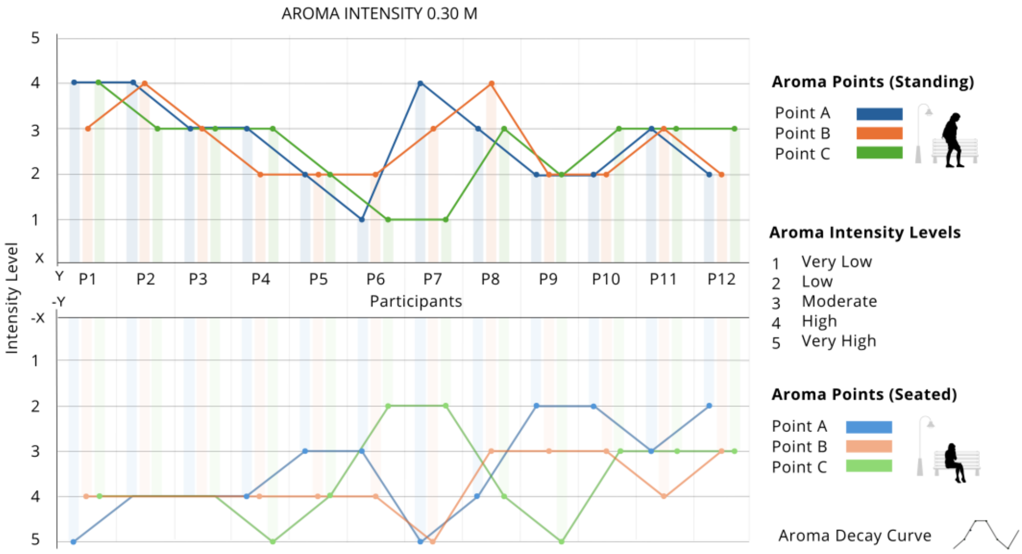


Figure 6. Aromatic intensity distribution at 0.30 m distance.

At 0.60 m, a progressive decrease in aromatic intensity is observed, with values predominantly between levels 2 and 3. Differences between evaluation positions are reduced, although the seated conditions still presents slightly higher perception levels (Figure 7).

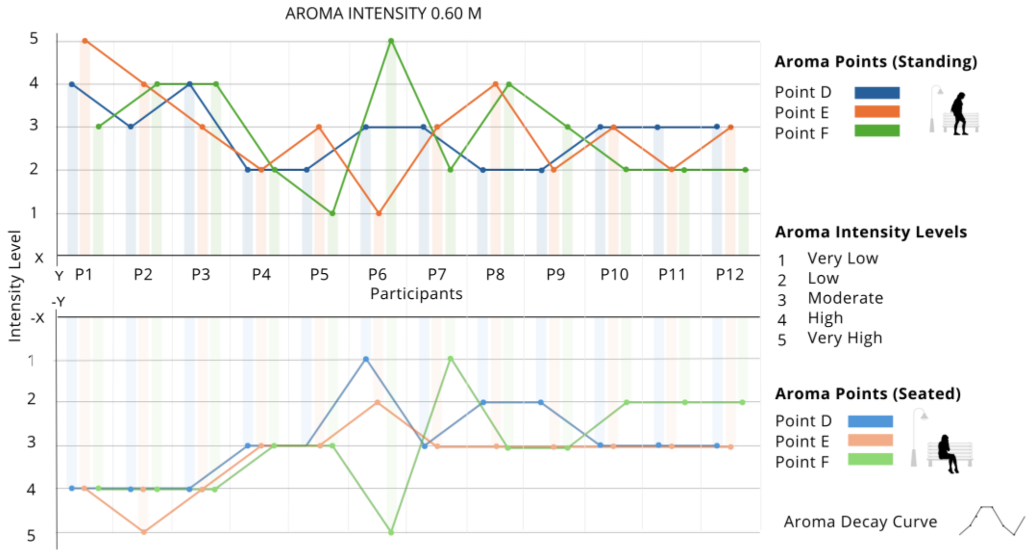


Figure 7. Aromatic intensity distribution at 0.60 m distance.

At 0.90 m, a more pronounced decrease in aromatic intensity is observed, with values mainly at level 2 and occasional peaks at level 3. Differences between positions are minimal, suggesting reduced aromatic perception at greater distances (Figure 8).

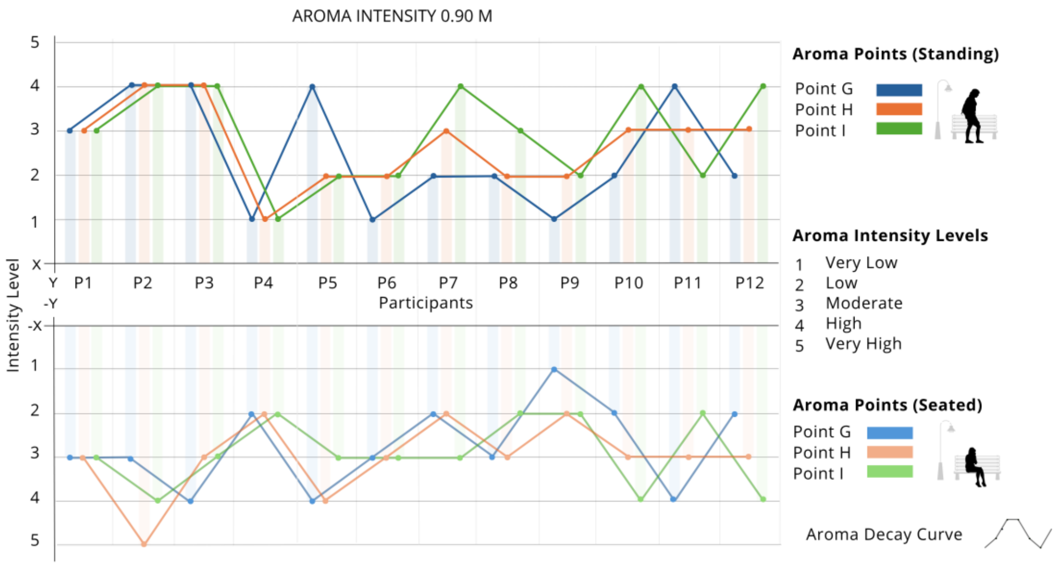


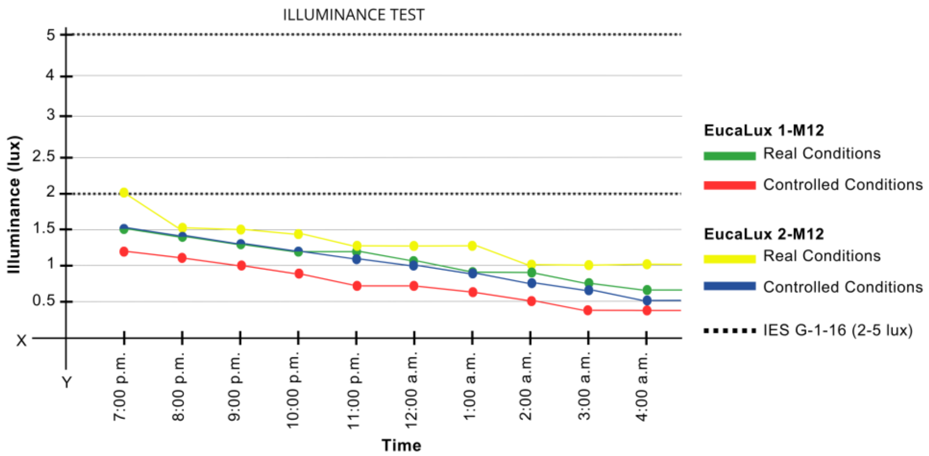
Figure 8. Aromatic intensity distribution at 0.90 m distance.

Overall, the results show a consistent decrease in aromatic intensity with increasing distance, maintaining perceptible emission within the evaluated range.

3.2. Photometric Performance

3.2.1. Illuminance

Illuminance results indicate that both types of EucaLux Bricks exhibit decreasing luminous behavior throughout the nighttime period (Figure 9).



Illuminance Test (lux)										
EucaLux 1-M12	**7 p.m.**	**8 p.m.**	**9 p.m.**	**10 p.m.**	**11 p.m.**	**12 p.m.**	**1 a.m.**	**2 a.m.**	**3 a.m.**	**4 a.m.**
Real Conditions	1,50	1,40	1,32	1,21	1,20	1,12	0,90	0,90	0,85	0,70
Controlled Conditions	1,20	1,15	1,00	0,92	0,85	0,80	0,70	0,50	0,30	0,26
EucaLux 1-M12										
Real Conditions	2,00	1,52	1,50	1,41	1,32	1,30	1,26	1,00	1,00	1,00
Controlled Conditions	1,50	1,42	1,30	1,22	1,10	1,00	0,92	0,72	0,60	0,50

Figure 9. Illuminance variation over time under nighttime conditions.

Under real conditions, the EucaLux 1-M12 brick presents initial values close to 1.5 lux, gradually decreasing to approximately 1 lux over time. In contrast, the EucaLux 2-M12 brick shows initial values close to 2 lux and maintains levels between 2 and 1 lux more consistently (Figure 10)

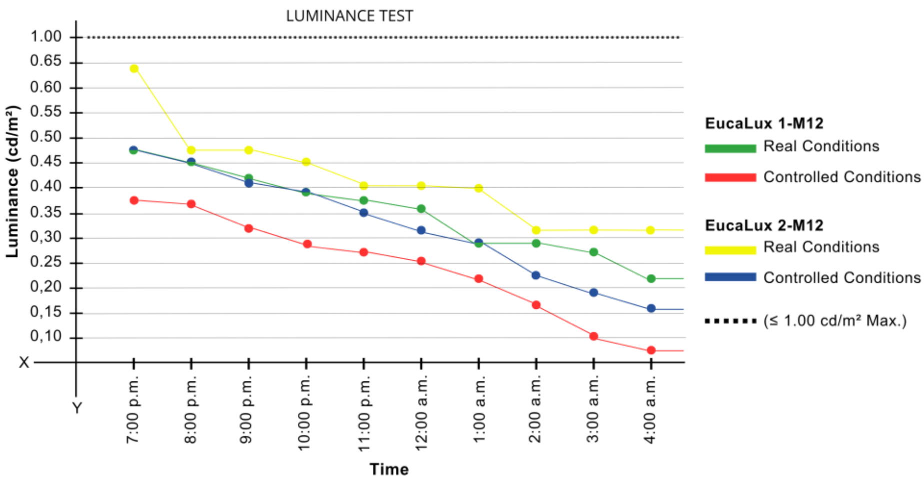
Figure 10. Comparison of illuminance performance between EucaLux prototypes.

Under controlled conditions, both types of EucaLux bricks exhibit a gradual reduction in illuminance, maintaining a consistent trend throughout the evaluation period.

These results indicate that both prototypes produce measurable illumination under nighttime conditions, with more stable behavior observed in the EucaLux 2-M12.

3.2.2. Luminance

Luminance values show a progressive decrease during the nighttime evaluation period for both types of EucaLux Bricks (Figure 11).



Luminance Test (cd/m²)										
EucaLux 1-M12	7 p.m.	8 p.m.	9 p.m.	10 p.m.	11 p.m.	12 p.m.	1 a.m.	2 a.m.	3 a.m.	4 a.m.
Real Conditions	0,48	0,45	0,42	0,39	0,38	0,36	0,29	0,29	0,27	0,22
Controlled Conditions	0,38	0,37	0,32	0,29	0,27	0,25	0,22	0,16	0,10	0,08
EucaLux 1-M12										
Real Conditions	0,64	0,48	0,48	0,45	0,42	0,41	0,40	0,32	0,32	0,32
Controlled Conditions	0,48	0,45	0,41	0,39	0,35	0,32	0,29	0,23	0,19	0,16

Figure 11. Luminance variation during nighttime evaluation.

Under real conditions, the EucaLux 1-M12 brick presents initial values of approximately 0.48 cd/m², decreasing to 0.22 cd/m². The EucaLux 2-M12 brick shows higher values, decreasing from approximately 0.64 cd/m² to 0.32 cd/m².

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Under controlled conditions, both materials exhibit lower values and a more pronounced decrease over time.

Overall, luminance values remain below 1 cd/m² throughout the evaluation period.

3.3. Physical Properties

3.3.1. Thermal Gain

Thermal evaluation results show a progressive increase in temperature during the morning hours, reaching peak values between 48 °C and 50 °C between 09:00 and 11:00 (Figure 12).

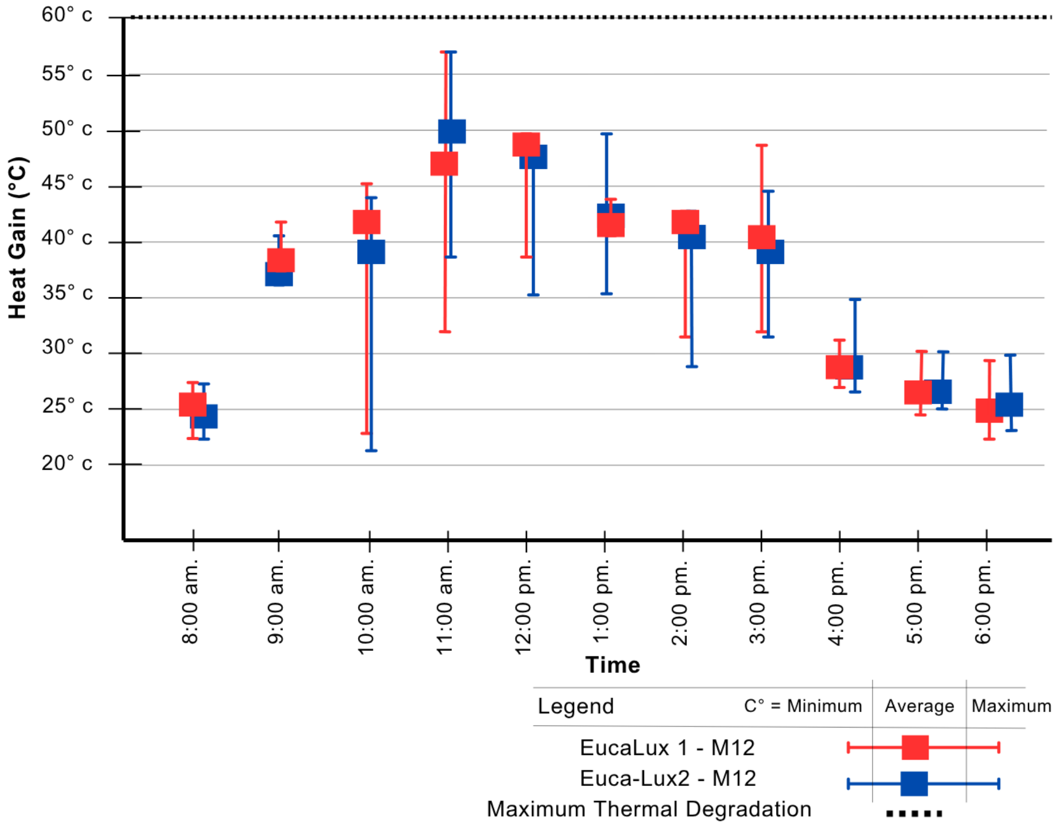

Figure 12. Thermal behavior of EucaLux bricks during daytime exposure.

The EucaLux 2-M12 brick presents slightly higher temperatures compared to EucaLux 1-M12, indicating greater thermal absorption. After reaching peak values, temperatures decrease gradually throughout the rest of the day.

3.3.2. Water Absorption

In the immersion-based water absorption test, the EucaLux 1-M12 brick shows variability among samples, with some specimens presenting higher absorption levels associated with surface fissures (Figure 13).

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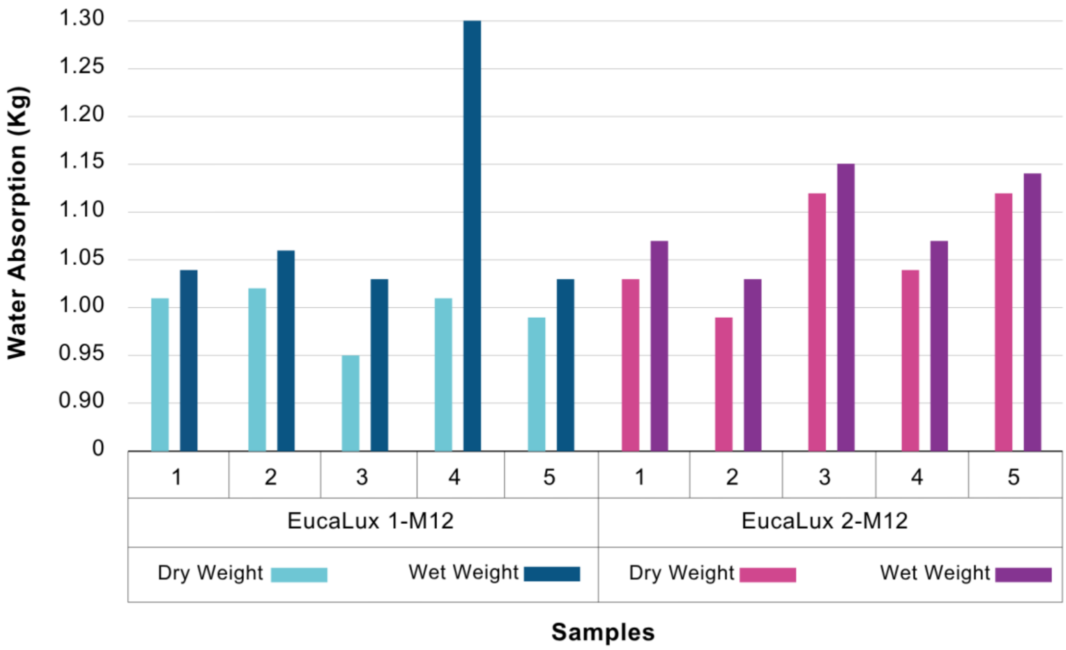

Figure 13. Water absorption behavior under immersion conditions.

In contrast, the EucaLux 2-M12 brick presents lower absorption values and more uniform behavior, indicating reduced permeability.

In the real rainfall exposure test, EucaLux 1-M12 exhibits variability between samples, whereas EucaLux 2-M12 maintains a more stable response (Figure 14).

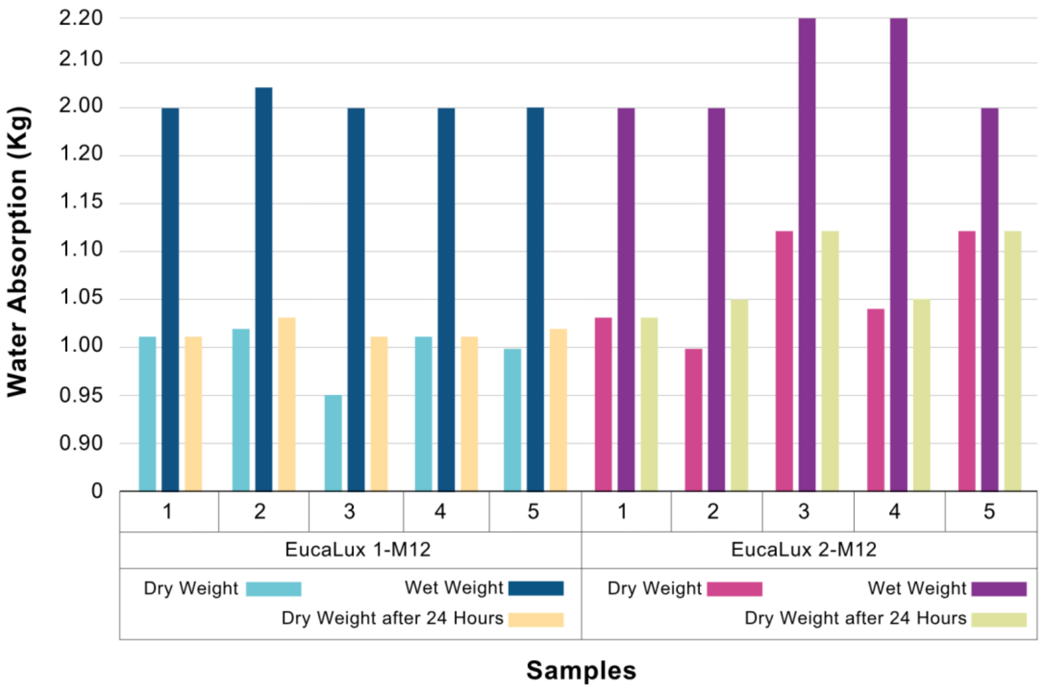

Figure 14. Water absorption behavior under real rainfall exposure.

3.3.3. Compressive Strength

The compressive strength analysis shows a progressive response of the material under increasing loads (Figure 15).

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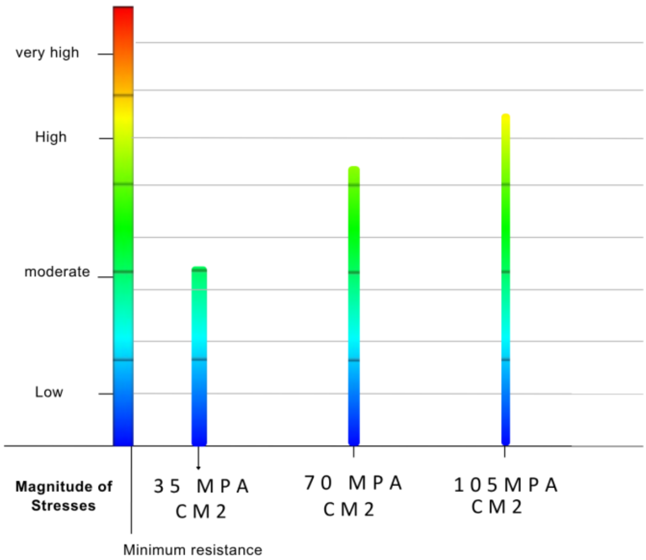

Figure 15. Stress distribution under compressive loads (35 MPa, 70 MPa, and 105 MPa).

At 35 MPa, stress concentrations are localized without visible structural damage. At 70 MPa, a wider distribution of stress is observed, indicating the onset of deformation. At 105 MPa, critical zones with visible cracking are identified, reflecting conditions close to the material's structural limit.

3.4. Application in Urban Space

The application of the EucaLux material in the design proposal for Melgar Park enabled its integration into pedestrian pathways and functional zones (Figure 16).

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Figure 16. Urban design proposal for Melgar Park integrating EucaLux sensory pathways: (a) modular system, (b) plan view, (c) spatial revitalization strategy, and (d) isometric representation.

4. Discussion

The results demonstrate that the integration of photoluminescent and aromatic properties into a single construction material represents a feasible strategy for enhancing the functionality and user experience of urban public spaces. In particular, the luminous performance of the developed bricks indicates their ability to provide passive illumination under nighttime conditions, with values approaching recommended ranges for low-activity pedestrian environments [19]. This behavior is consistent with previous studies highlighting the efficiency of strontium aluminate-based materials

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in storing and emitting light over extended periods [8,11]. However, unlike studies that focus primarily on photometric performance, the present research situates these properties within an urban design framework, where lighting serves not only a technical function but also a perceptual and spatial role.

From an urban perspective, the passive illumination provided by the EucaLux bricks can be interpreted as a complementary spatial guidance system, contributing to improved environmental legibility and perceived safety during nighttime use. This aligns with contemporary urban design approaches that emphasize the role of environmental perception in shaping user behavior and space appropriation, particularly in contexts with limited artificial lighting.

The incorporation of aromatic compounds introduces an additional sensory dimension that extends beyond conventional visual-based design strategies. The observed stability and functional range of aromatic release at short and medium distances are consistent with previous research on controlled emission of volatile compounds in porous materials [13,15]. Nevertheless, the main contribution of this study lies not only in the effectiveness of aromatic release but in its application as a spatial tool, capable of reinforcing orientation, generating sensory landmarks, and enhancing user experience.

The combination of luminous and olfactory stimuli supports a multisensory approach to urban design, moving beyond the traditional predominance of visual perception. This perspective is aligned with emerging research in environmental perception and neuroarchitecture, which advocates for the integration of multiple sensory inputs to improve comfort, accessibility, and inclusiveness in public spaces [22,23]. In this context, the developed sensory materials can be understood as active components in shaping spatial experience, influencing how users perceive, navigate, and interact with urban environments.

From a sustainability standpoint, the use of recycled materials in the fabrication process contributes to reducing the environmental impact associated with construction waste and promotes the use of local resources, consistent with circular economy principles [5,6]. Additionally, the implementation of passive lighting strategies reduces reliance on energy-intensive urban lighting systems, potentially lowering energy consumption and associated emissions. This dual contribution—material and energetic—reinforces the sustainable character of the proposed solution.

Regarding physical performance, the results indicate that the developed EucaLux Bricks exhibit adequate mechanical resistance, controlled water absorption, and stable thermal behavior, supporting their applicability in outdoor urban environments. The improved performance observed in the EucaLux 2-M12 configuration suggests that homogeneous integration of functional components enhances material stability, consistent with findings in previous studies on composite materials [6,11].

The application of the material in the Melgar Park case study further illustrates its potential as a tool for urban revitalization. The integration of sensory pathways within the spatial organization contributes to structuring movement, supporting diverse activities, and enhancing the overall quality of the public space. In this sense, the study demonstrates that material innovation can extend beyond technical performance to influence spatial configuration and urban dynamics.

Despite these contributions, the study presents some limitations. The sensory evaluation was conducted with a limited number of participants, which may influence variability in perception. Additionally, although tests were performed under real conditions, long-term performance of the material was not assessed. Future research should include longitudinal studies to evaluate durability under different environmental conditions, as well as broader user-based assessments to better understand the impact of sensory materials on urban experience and behavior.

5. Conclusions

This study demonstrates the feasibility of integrating photoluminescent and aromatic properties into a functional construction material, resulting in a multisensory system applicable to the sustainable revitalization of urban public spaces. The developed EucaLux Bricks exhibit adequate luminous, aromatic, and physical performance, supporting their suitability for implementation in real urban environments.

Beyond their technical performance, the main contribution of this research lies in positioning sensory materials as active elements in urban design. The integration of luminous and olfactory stimuli expands conventional approaches to public space design by enhancing orientation, perceived safety, and user experience, particularly under nighttime conditions.

From a sustainability perspective, the use of recycled materials and the implementation of passive lighting strategies contribute to reducing environmental impact and improving resource efficiency. This approach highlights the potential of the proposed materials as innovative solutions within sustainable urban design frameworks.

Furthermore, the application of the material in the Melgar Park case study illustrates how material innovation can extend beyond construction to influence spatial configuration, promoting more inclusive, dynamic, and active use of public space.

Overall, this study contributes to bridging material science and urban design through a multisensory approach, proposing a novel direction for the development of more sustainable, perceptive, and inclusive urban environments.

6. Patents

The material innovation developed in this study is currently the subject of a patent application filed with the National Institute for the Defense of Competition and Protection of Intellectual Property (INDECOPI), Peru. The invention, entitled "Aromatic Construction Block for Nocturnal Urban Signaling and Illumination", has been submitted under application number 002271-2025/DIN.

The invention is classified under the International Patent Classification (IPC) codes B05D 3/00 and B29C 39/00 and covers the formulation and integration of photoluminescent and aromatic functionalities into construction materials aimed at enhancing urban visibility, orientation, and sensory experience in public spaces.

Supplementary Materials: The following supporting information can be downloaded at: Preprints.org.
Figure S1: EucaLux brick fabrication process, including material preparation, molding, and curing stages;

Table S1: Complete dataset of illuminance and luminance measurements under real and controlled conditions;
Table S2: Odor Activity Value (OAV) measurements at different distances (0.30 m, 0.60 m, and 0.90 m) and user positions;
Table S3: Physical properties dataset, including water absorption, and thermal gain.

Author Contributions: Conceptualization, R.L. and N.A.; methodology, V.I.; software, R.L. and N.A.; validation, V.I..; formal analysis, R.L. and N.A.; investigation, R.L., N.A. and V.I.; resources, R.L. and N.A.; data curation, R.L. and N.A.; writing—original draft preparation, R.L. and N.A.; writing—review and editing, V.I..; visualization, R.L. and N.A.; supervision, V.I..; project administration, R.L. and N.A.; funding acquisition, R.L. and N.A. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Ethical review and approval were waived for this study because the sensory evaluation involved non-invasive procedures, did not include vulnerable populations, and did not collect personal or sensitive data. All participants were informed about the purpose of the study and provided voluntary consent prior to participation.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.
Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

OAV	Odor Activity Value
IES	Illuminating Engineering Society
ASTM	American Society for Testing and Materials
NTP	Norma Técnica Peruana
ISO	International Organization for Standardization
IPC	International Patent Classification

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