FACTA UNIVERSITATIS
Series: **Architecture and Civil Engineering** Vol. 23, Nº 1, 2025, pp. 33 - 49
https://doi.org/10.2298/FUACE240423005M

Original research paper

GREEN CORES POSITIONING IN ENERGY GENERATING RESIDENTIAL UNITS

UDC 628.92/.921

Marko Mihajlović[1], Ingrid Paoletti[2], Milan Dragoljević[2]

[1]Department of Architecture, Faculty of Technical Sciences, Novi Sad, Serbia
[2]Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Italy

ORCID iDs: Marko Mihajlović N/A
Ingrid Paoletti https://orcid.org/0000-0002-4169-6126
Milan Dragoljević https://orcid.org/0000-0002-3027-4884

Abstract. *This study explores a methodological approach to architectural design by introducing the concept of green cores, while optimizing lighting schemes within residential architecture to foster the building's metabolism in this innovative system operating as a dynamic interplay between architectural design, sustainable energy generation, and biological processes. It unravels the complex interplay of light dynamics and environmental variables essential for effective energy generation and plant growth. The research seeks to explore interior spaces as dynamic ecosystems that foster environmental sustainability, for accommodating human habitation within urban ecosystems, resulting in showcasing optimal greenery positions for a holistic approach. Having scientific principles behind this integration of nature and technology, this research aims to understand the foundation for biophilic practices in contemporary architecture. Furthermore, this research serves as a precursor for further investigations and possible usage of Plant Microbial Fuel Cells (PMFC) in architecture design. It was developed under the research through design approach.*

Key words: *spatial structuring, light dynamics, environmental variables, urban ecosystems, nature integration, plant microbial fuel cells.*

1. INTRODUCTION

The field of architecture is experiencing a significant paradigm shift, embracing the synergy between natural elements and the built environment (Kellert, 2018). In this transformative era, architects and designers are reimagining the traditional boundaries by incorporating nature-centric designs within residential spaces (Mazzoleni, 2013). The

Received April 23, 2024 / Revised June 22, 2024 / Accepted August 5, 2024
Corresponding author: Marko Mihajlović - University of Niš, Faculty of Technical Sciences, Novi Sad, Serbis
e-mail: mihajlovic_marko@uns.ac.rs

integration of living organisms, particularly vegetation, has sparked a new wave of architectural innovation, blurring the lines between indoors and the natural world. Previous works have demonstrated the feasibility and advantages of introducing vegetation into residential units (Poincelot & Flagler, 2018). Beyond merely adding vegetation as an aesthetic element which was a primal intention in the past, these integrations have evolved to provide functional benefits as well, such as improved indoor air quality, psychological well-being, and temperature regulation.

The whole system integrated into residential spaces represents a revolutionary approach aligning with multiple Sustainable Development Goals (SDGs), addressing several targets under each goal (UN, 2015). Achieving SDG 11 - Sustainable Cities and Communities, the system supports the development of eco-friendly urban spaces. It contributes to creating sustainable infrastructure by incorporating nature-based solutions into residential design, fostering green and resilient communities. Within SDG 11, the target of providing universal access to safe, inclusive, and accessible green spaces is met through the incorporation of nature-centric designs into residential units. In terms of SDG 13 - Climate Action, this is important in mitigating carbon emissions (IEA 2018). Scalability of this system could potentially provide the reduction of the carbon footprint of households, directly addressing climate change concerns. Moreover, the system aligns with SDG 15 - Life on Land, emphasizing the importance of integrating natural elements into architecture. It promotes biodiversity and ecosystem health, contributing to a more harmonious coexistence between humans and nature within urban settings. In line with SDG 15, the target to protect, restore, and promote the sustainable use of terrestrial ecosystems is supported by enhancing the role of plants within urban environments.

An important element of this approach lies in its essence as a nature-based solution centered on human needs. This paradigm shift redefines the role of nature within architectural frameworks, aligning it intricately with anthropocentric goals (Sustainable Development Goals: Law, Theory and Implementation n.d.). The integration of natural elements, especially vegetation, within residential spaces is not merely ornamental but serves a fundamental purpose: enhancing human well-being. The implementation of nature within these spaces is meticulously designed to cater to human comfort, health, and productivity. It is a testament to the inherent synergy between nature and human-centric designs, where the natural world becomes an integral part of a harmonious living environment, offering tangible benefits while seamlessly serving the needs of its inhabitants. This harmony of nature and human-centered design incorporates a visionary approach that transcends the traditional dichotomy between urban living and the natural world.

Further advancements in this domain are poised to revolutionize energy harnessing within residential environments. Plant Microbial Fuel Cells (PMFCs) represent a promising avenue for sustainable energy generation (Slattery and Ort 2021). PMFCs utilize microbial activity in soil to convert organic matter into electrical energy, effectively transforming residential units into active energy generators. This process involves microbes breaking down organic compounds during photosynthesis, releasing electrons that are captured by electrodes. Typically, the system comprises an anode buried in the soil, where anaerobic conditions favor microbial activity, and a cathode exposed to the air, where oxygen reduction occurs. The electrons flow from the anode to the cathode through an external circuit, generating electricity. Integrating PMFCs within the green cores of residential spaces enhances energy autonomy and strengthens the symbiotic relationship between humans and nature. The green cores serve as both aesthetic and functional components, housing PMFC systems that continuously generate renewable energy. The energy generated, dependent on the amount stored could be used to enhance the system functioning and as a future investment in plants health, outlining the sustainability element. Future research can explore optimizing PMFC performance, increasing energy yield, and integrating PMFC technology seamlessly into architectural designs. By fostering collaboration between architects, engineers, and biologists, PMFCs can transfigure sustainable living environments of architecture design.

2. THEORY

The integration of natural components within architectural designs, specifically the incorporation of green cores, marks a paradigmatic shift in contemporary architectural discourse (Roaf et al. 2009). The term green cores as a structural element of interior design in this context is coined throughout this paper. It is presenting a natural element but also a component which could be crucial within the building structure, minoring the boundaries between the built and natural environment. Green cores integrate vegetation within the architectural framework, serving as functional ecosystems that support biodiversity and improve air quality. These cores are designed to harmonize with the structural elements, ensuring stability while enhancing the aesthetic and environmental quality of the living spaces, standing either as a single unit or within a multifunctional interior module. By incorporating plants that thrive under specific interior conditions, green cores promote sustainable living practices and contribute to the overall well-being of the occupants, merging the benefits of nature with advanced architectural design. The transformative approach seeks to redefine the conventional boundaries of architectural practice. (Jensen, 2017) One key concept shaping this theoretical framework is the notion of "Building's Metabolism." In this innovative architectural design, green cores are strategically positioned to optimize the process of photosynthesis. This strategic placement introduces a dynamic element into the architectural narrative, where living organisms play a vital role in the metabolic processes of the building. The green zone, deliberately juxtaposed against traditional day and night zones, symbolizes a holistic approach that considers the delicate balance of proportions, microclimate, and spatial structuring (Advances in Human Factors and Sustainable Infrastructure 2016). The aim is to ensure a harmonious integration of nature and architecture, forging ecosystems within the confines of built environments.

Within the previously mentioned materials, the emphasis is not solely on the technological aspects but on the broader ecological implications of such integrations. The green cores become dynamic components contributing to the building's overall metabolism, influencing energy flows, air quality, and even the psychological well-being of its occupants. This holistic approach transcends the traditional dichotomy between the artificial and the natural, fostering a symbiotic relationship between the built environment and the ecosystems it contains. In essence, the Building's Metabolism concept champions a new era in architectural thinking — one that considers the built environment as a living entity with its own metabolic processes (Adler and Tanner, 2013). By that, the methodology nurtured throughout the paper has a significant holistic impact in the data collection. The green cores act as catalysts for this metabolic activity, redefining the role of architecture in nurturing ecosystems. As we delve into the intricacies of this theoretical framework, it becomes evident that the integration of nature within architecture is not just a technological endeavor; it is a philosophy that harmonizes the built environment with the rhythms of the natural world, bringing forth a sustainable and symbiotic coexistence (Biological Control of Invasive Plants in the Eastern United States, 2002).

2.1. Overview of Recent Research

Research suggests that a neutral average lux range between 500 and 1500 lux corresponds to a balanced illuminance level beneficial for a diverse array of plant species and growth stages (Yong et al., 2017). This range ensures adequate photosynthetic activity without the risk of overexposure, which can lead to photoinhibition or excessive transpiration. Additionally, studies have shown that variations in lux levels can influence specific growth parameters such as leaf morphology, flowering time, and overall biomass production (Poorter et al., 2012). Understanding these nuances allows for more precise control over the growing environment, ultimately enhancing crop yields and quality. Recent advancements in lighting technologies and building materials have enabled more sophisticated manipulation of daylight within indoor environments. For instance, the integration of dynamic shading systems and light-diffusing materials can modulate the intensity and distribution of natural light, creating optimal conditions for plant growth and human comfort alike (Qin, et al., 2014). These innovations underscore the importance of interdisciplinary research and collaboration between architects, engineers, and plant scientists to develop sustainable and efficient indoor lighting solutions. In the context of horticulture and urban farming, precise control over light exposure is critical. Modern greenhouses and indoor farming setups now often employ automated systems that adjust artificial lighting based on real-time measurements of natural light levels, ensuring that plants receive consistent and optimal illumination throughout the day (Yang et al., 2022). This blend of natural and artificial lighting strategies not only enhances plant growth but also contributes to energy efficiency and sustainability. The synthesis of these findings emphasizes the critical role of tailored lighting strategies in both architectural design and plant cultivation. By leveraging detailed lux value analyses and innovative lighting technologies, it is possible to create indoor environments that are both energy-efficient and conducive to the health and productivity of plant species.

3. Methodology

By employing a comparative methodology, an extensive examination was carried out to explore lux values in each of the distinct approaches of the various orientations, aiming to deepen comprehension of natural light dynamics in interior settings. Lux values were systematically investigated for each side in all scenarios, and it was concluded that it could be generalized this way, by summation of lux values. As depicted in Figure 1, lux values across various orientations were systematically investigated, aiming to deepen comprehension of natural light dynamics in interior settings. This involved a methodological workflow encompassing steps firstly to optimize space configuration, and overlay the variously oriented annual daylight analysis. Then collected data could be used further for general assessment.

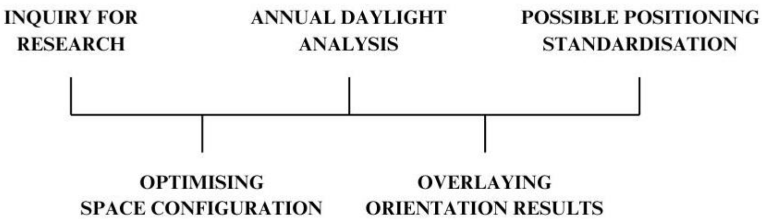

Fig. 1 Methodological research workflow

3.1. Determining the Daylight Impact

Effective environmental lighting analysis is pivotal for the successful integration of plants within interior spaces, particularly concerning their growth and sustenance (Kellert, 2018; Binggeli & Greichen, 2011). The conducted research was carried out in Belgrade, Serbia, on situated in the Northern Hemisphere. The study area experienced overcast sky conditions, relevant for analyzing the Daylight Factor Effective Area, and average sky conditions for assessing lux values. The zenith luminance was measured at 3917 cd/m2, providing insight into the ambient lighting conditions. The research considered medium to heavy traffic pollution and dust exposure levels below 600 micrograms per cubic meter, characteristic of the urban environment. These environmental parameters were essential for understanding how natural daylight interacts with interior spaces and vegetation within the specified context. The study encompassed a range of room dimensions and geometries, including various sizes and proportions. It delves into the process of light calculation, exploring daylight factors, average lux measurements, room dimensions, window types, and orientations to evaluate the spatial distribution and intensity of light (Siniscalco 2021). To capture a wide range of conditions, data collection was conducted across various configurations, including different window orientations, sizes, and positions. These configurations were meticulously recorded to ensure accurate analysis and replicability. Figure 2 illustrates some of the examples of the comparative methodology used in the study, depicting the systematic examination of different orientations, window positions, and room proportions and many other variables. The diagram visually represents the experimental setups and their impact on light penetration, highlighting

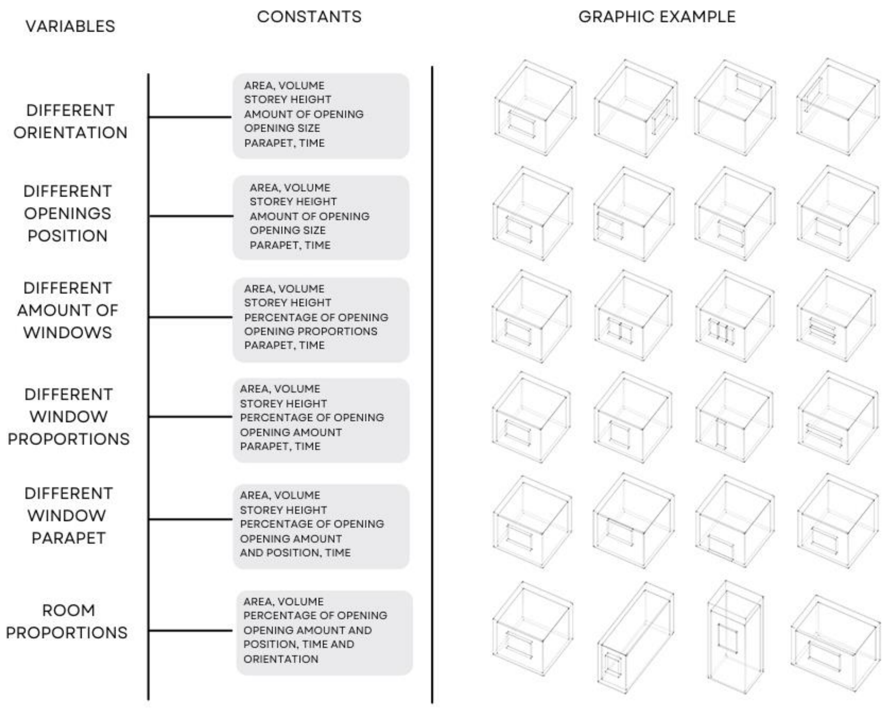

Fig. 2 Comparative methodology for assessing lux values in different room configurations

the importance of centralized window positions, optimal window-to-wall ratios, and room proportions on natural light distribution. This visual aid underscores the significance of tailored design strategies to enhance natural light in residential spaces.

This finding implies that the aggregation of lux values within a singular, well-designed space offers a more versatile lighting framework. This generalization carries implications for architects and designers, providing a streamlined and adaptable approach to optimizing natural light penetration in various residential settings during a process of architectural design.

The objective of these insights is not only to optimize the conditions for plant growth but also to harmonize optimal human conditions with the constraints of maximizing the photosynthesis efficiency. In residential environments, striking a balance between human well-being and the thriving vitality of indoor plants hinges on understanding environmental conditions. This equilibrium requires an ambiance that caters to both human comfort and the optimal growth of plant life. Central to achieving this steadiness is the examination of key lighting metrics: the Day Factor Effective Area, Average Lux, and Photosynthetically Active Radiation (PAR). The Day Factor Effective Area illuminates the distribution of natural daylight within a room, identifying specific areas where light intensity meets or exceeds predetermined thresholds (Trivellini et al., 2023). This knowledge is pivotal for strategic plant placement and ensuring uniform light dispersion, vital for healthy plant growth (Karslı, 2013). Complementing this, the Average Lux measurement offers a comprehensive assessment of overall light intensity, critical for creating conditions conducive to robust plant ecosystems (Eviner & Hawkes, 2008). It is crucial as it directly affects the metabolic processes within plants. In conjunction with these metrics, the study also delves into Photosynthetically Active Radiation (PAR), which encompasses the spectral range of solar radiation essential for plant photosynthesis (Bula et al., 1991). This metric directly influences plant growth, development, and overall health. Understanding optimal PAR levels within residential spaces is fundamental for ensuring adequate light exposure to support plant growth. Strategic integration of artificial lighting systems emitting PAR wavelengths further supplements natural light, fostering an environment conducive to photosynthesis. Each metric was analyzed using advanced simulation software, such as DIALux, to model light behavior under different scenarios. These simulations provided a detailed understanding of how light interacts with various architectural elements, enabling precise adjustments to improve light distribution.

Through an in-depth analysis of the Day Factor Effective Area, Average Lux measurements, and PAR, this research endeavors to unravel the important relationship between light dynamics, human habitation, and indoor plant vitality. In essence, PAR ensures the availability of light wavelengths essential for photosynthesis, average lux measures the overall brightness impacting plant metabolic processes, and the Day Factor Effective Area assists in ensuring uniform light distribution essential for optimal plant growth and health in residential spaces provide insights that inform the design of spaces capable of accommodating human comfort while nurturing residential ecosystems (Kellert, 2005). The study's findings emphasize the significance of balancing natural and artificial lighting to maintain optimal conditions for both plants and humans. By integrating these insights into architectural design, it is possible to create environments that are not only aesthetically pleasing but also functionally efficient for sustaining plant life and enhancing human well-being.

In conclusion, a thoughtful combination of orientations, with a focus on achieving a balanced and consistent lux distribution, is crucial for successful vegetation implementation.

The East and West orientations emerge as promising options, providing moderate average lux values conducive to plant health without the potential drawbacks of excessive exposure. Strategic planning and consideration of the specific lux requirements for different plant species can further enhance the success of vegetation implementation in interior spaces (Advances in Human Factors and Sustainable Infrastructure, 2016). The detailed examination of various configurations, such as those presented in Figure 3, provides a robust framework for understanding the dynamic variables of light penetration in interior spaces, showing that combined orientations would be more optimal regarding quality and quantity of light in comparison to North, South, West and East.

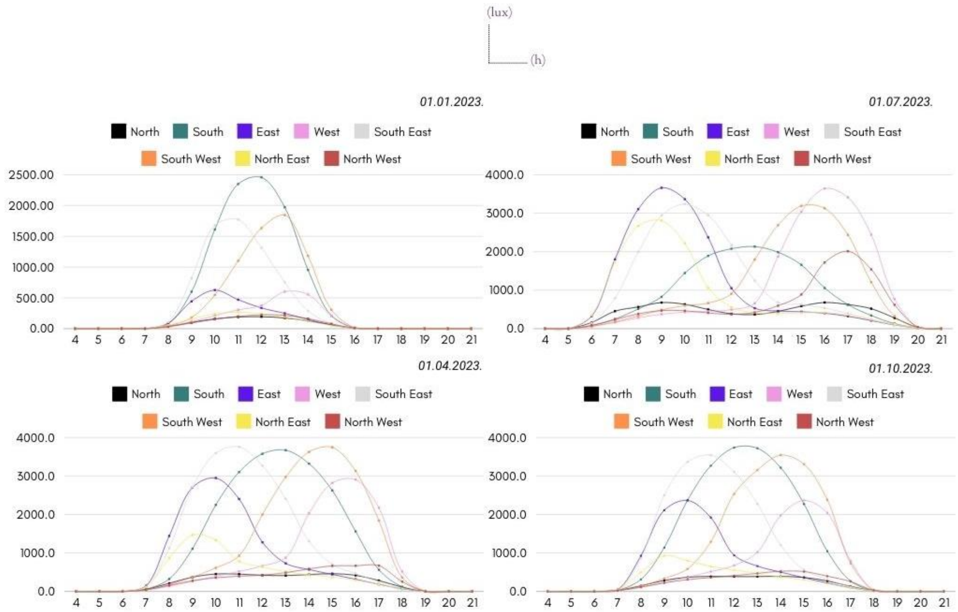

Fig. 3 Diagram showing dynamic variables of light penetration simulated via DIALux

4. RESULTS

4.1. Architectural Prerequisites

The analysis examines the impact of various environmental factors on light penetration within residential spaces, crucial for plant growth (Ong, 2003). Each segment considers different configurations, such as window orientation, size, proportion, and room dimensions, to evaluate their effects on the Day Factor (DF) effective area and average light penetration. A comprehensive analysis was conducted using advanced simulation tools to model these configurations accurately, ensuring that the data reflects real-world scenarios.

In tandem with these architectural considerations, the integration of Plant Microbial Fuel Cells (PMFCs) introduces a groundbreaking approach to energy generation within residential environments. PMFCs harness the natural microbial activity present in soil to convert organic matter into electrical energy, offering a sustainable and renewable energy solution. The technical aspect of PMFC implementation involves optimizing factors such as soil composition, electrode materials, and microbial diversity to maximize energy output while ensuring long-term stability and efficiency. Research efforts focus on enhancing PMFC performance through innovations in electrode design, microbial engineering, and system integration.

Moreover, the Daily Light Integral (DLI) calculations reveal diverse light levels received by plants based on lux values and the assumption that 50% of the light falls within the photosynthetically active radiation (PAR) spectrum. This data highlights the varying light exposure potential for plants in different orientations: from low to high-light plants, each requiring specific DLI ranges for optimal growth (Bula et al., 1991). Detailed measurements of lux values at various times of the day and across different seasons were taken to ensure a comprehensive understanding of light exposure patterns. The analysis further delves into the impact of window proportions and room dimensions on light penetration. It indicates that larger windows or windows with wider walls receive more natural light, essential for supporting plant photosynthesis. The centralization of openings and the dynamics between walls and windows were also explored to understand their impact on natural daylight penetration. However, maintaining a balance is crucial, as overly large windows might lead to challenges in temperature control and potential overexposure to direct sunlight. Additionally, variations in storey height and wall ratios significantly influence the Day Factor (DF) effective area and average light penetration. Higher ceilings tend to offer more uniform light distribution, favoring plant growth. Similarly, specific wall ratios reveal differences in average light penetration, emphasizing the importance of wall dimensions in achieving optimal lighting conditions.

Square windows are identified as the optimal choice, emphasizing their potential to offer a higher DF effective area, pivotal for supporting plant photosynthesis. Alongside this, lux values play a crucial role in assessing actual light intensity, a critical factor influencing plant growth. In cases of spaces with high ceilings, a preferable option lies between the parapet of the window of the optimal values, given that higher windows tend to provide more favorable lighting conditions. Spaces with larger window-to-wall ratios tend to receive increased natural light. However, an important caveat emerges as excessively large windows might pose challenges in regulating internal temperatures and lead to potential overexposure to direct sunlight, necessitating a delicate balance in design considerations. Wider openings in walls demonstrate a superior advantage, particularly in spaces with a square room layout, emphasizing the importance of space design in influencing lighting conditions. The analysis suggests an optimal storey height that balances lighting effectiveness with spatial dimensions. Additionally, exploring the optimal wall ratios highlights their potential to maximize lighting conditions within a given space.The findings suggest a preference for specific window dimensions and ratios to maximize interior light penetration. The larger the window, the more significant the light penetration, but careful consideration is necessary to strike the right balance between adequate light exposure and potential drawbacks of excessive sunlight. This analysis elucidates the intricate relationship between environmental variables and light penetration within residential spaces, underscoring the critical role of these factors in fostering an optimal environment for indoor plant growth and vitality (Foster, 1994). The evaluation of centralized opening positions indicates a distinct favorability towards such placements, showcasing comparable ratios across various percentage distributions. This observation underscores the significance of centralized openings in maintaining consistent lighting conditions within a space. While comparing single and multiple openings, a critical distinction emerges: a single opening presents a higher effective daily value, while multiple openings result in a higher average illumination. A comparative analysis of different opening configurations was performed, demonstrating the trade-offs between single and multiple openings regarding light distribution and intensity. The inconsistency raises a pertinent question regarding the importance of average illumination versus effective daily value concerning plant health and growth optimization.

The deliberate steps in construction implementation encompass crucial elements for optimal environmental conditions within residential spaces (Memari et al., 2014). These steps involve centralizing openings, allowing for either a single or two openings of identical area, with a preference for square window designs. Emphasizing a parapet input of values between 1.0m or 1.25m contributes to efficient lighting distribution, along with positioning the opening on the wider wall. A 3m storey height is identified as an optimal factor for 25sqm area and 4sqm centralized opening, balancing vertical space and light exposure. The suggested wall ratios of 1:1.25 or 1:1.6 reflect an ideal proportion between wall space and window area. Additionally, a specific window orientation ratio of W:E:S:N = 1:0.98:3.73:0.41 calculating a balance across different orientations, crucial for understanding exact same lighting levels throughout the living space connected to construction. These guidelines were derived from a combination of empirical data and theoretical models, ensuring practical applicability in real-world construction projects. These detailed construction guidelines are instrumental in creating spaces that promote both human comfort and the thriving growth of indoor plants.

Through the implementation of a comparative methodology, a thorough investigation of lux values within two distinct approaches was conducted to enhance the understanding of natural light dynamics in interior spaces. In the first approach, two different spaces, each featuring a single window oriented on two sides, were scrutinized. The second approach focused on a unitized single space with dual orientations. Lux values were systematically researched for each side in both scenarios. Notably, an insightful revelation emerged from the analysis: the sum of lux values from each side within the unique unit demonstrated a broader application spectrum. This generalization provides a flexible framework for architects and designers, allowing for adaptable solutions in various residential settings.

What is compelling regarding the combination of the sun and vegetation is that greenery while being put in front of the windows can act as a natural temperature regulator for the interior ambiance. This symbiotic relationship between vegetation and sunlight creates a natural brise soleil effect, with foliage reaching its peak during summer to shield apartments from intense heat, and shedding foliage during winter to allow sunlight to penetrate the interior space. A natural brise soleil, reaching the height of its vegetation during the summer months, protects the apartments from the intense heat of the day, and sheds most of its foliage during the winter months, allowing the sun to penetrate as much as possible of the interior space. As a final product, the residential units in multi-family buildings, based on all the previous conclusions and analyses, would result in housing units that are optimally designed to provide the best conditions for both, users and vegetation.

4.2. Strategic Positioning of Green Cores

This phase of the study delves into optimizing the integration of green cores, emphasizing scientifically derived principles for optimal plant growth and overall environmental well-being. Building upon the lighting insights established in the previous analysis, this exploration ventures into the interplay between spatial design, lighting dynamics, and the placement of green cores. By aligning these components, we aim to not only create aesthetically pleasing indoor landscapes but to also foster a harmonious coexistence where the built environment enhances the vitality of plant life. The integration of green cores, strategically positioned based on rigorous scientific evaluations, stands poised to revolutionize the way we conceptualize and design residential spaces, ushering in an era where architecture seamlessly integrates with the natural world for the benefit of both inhabitants and indoor ecosystems.

In pursuit of optimizing lighting schemes within green cores of residential ecosystems, a methodologically rigorous approach was undertaken. The study focused on previously understood measurements, and given that, a standardized room sample was taken as a base with square geometry (25 sqm, 5x5 meters room), a single window (2x2 meters), 3 meter storey height, and a 1 meter parapet. The temporal analysis is taking into consideration lux values throughout 24 hours span for the whole year. The room was systematically segmented into an 10x10 grid, resulting in 100 distinct points for average lux measurement at different times and orientations. Lux values, indicative of light intensity, were meticulously collected, employing advanced sensors and simulation tools. The data underwent thorough analysis, utilizing statistical tools to identify patterns and correlations. Simultaneously, simulations and modelling techniques contributed to extrapolating findings beyond the specific room sample, ensuring broader applicability. A validation process scrutinized the consistency of results across scenarios, orientations, and timeframes.

From the analysis conducted, average lux values were extracted to formulate optimal positions for green cores within the designated space. This involved synthesizing data from multiple points, times, and orientations, culminating in a comprehensive understanding of the average lighting conditions. The consideration of optimal lux values for plant growth played a pivotal role in determining suitable positions within the space. The scientific literature underscores the importance of adequate lighting for plants, affecting photosynthesis, metabolic processes, and overall vitality. Optimal lux values range between 500 and 1500 average daily lux, striking a balance that supports robust photosynthesis and growth while avoiding potential issues related to overexposure. The positioning of green cores within the space was strategically derived to ensure not only optimal light exposure but also consideration of ambient air quality and temperature. This holistic approach aligns with the principles of biophilic design, fostering a symbiotic relationship between nature and the built environment (Zhong et al. 2023). The chosen lux values and positioning parameters represent a significant contribution to the scientific understanding of creating balanced residential ecosystems. Achieving an optimal synergy between temperature regulation and lighting conditions is paramount for the successful integration of green cores in residential ecosystems. The analysis indicates that for the specified temperature range of 18 to 24 degrees Celsius, plants within the designated space would benefit from higher light levels. In alignment with the principles of biophilic design, the strategic positioning of green cores was calibrated to ensure an average daily lux value between 500 and 1500. This range not only caters to the enhanced metabolic activity of plants within the specified temperature parameters but also fosters an environment conducive to robust photosynthesis and growth. These findings are visually represented in Figure 4, which illustrates the analysis of average annual lux values and the optimal positioning of green cores within the designated space.

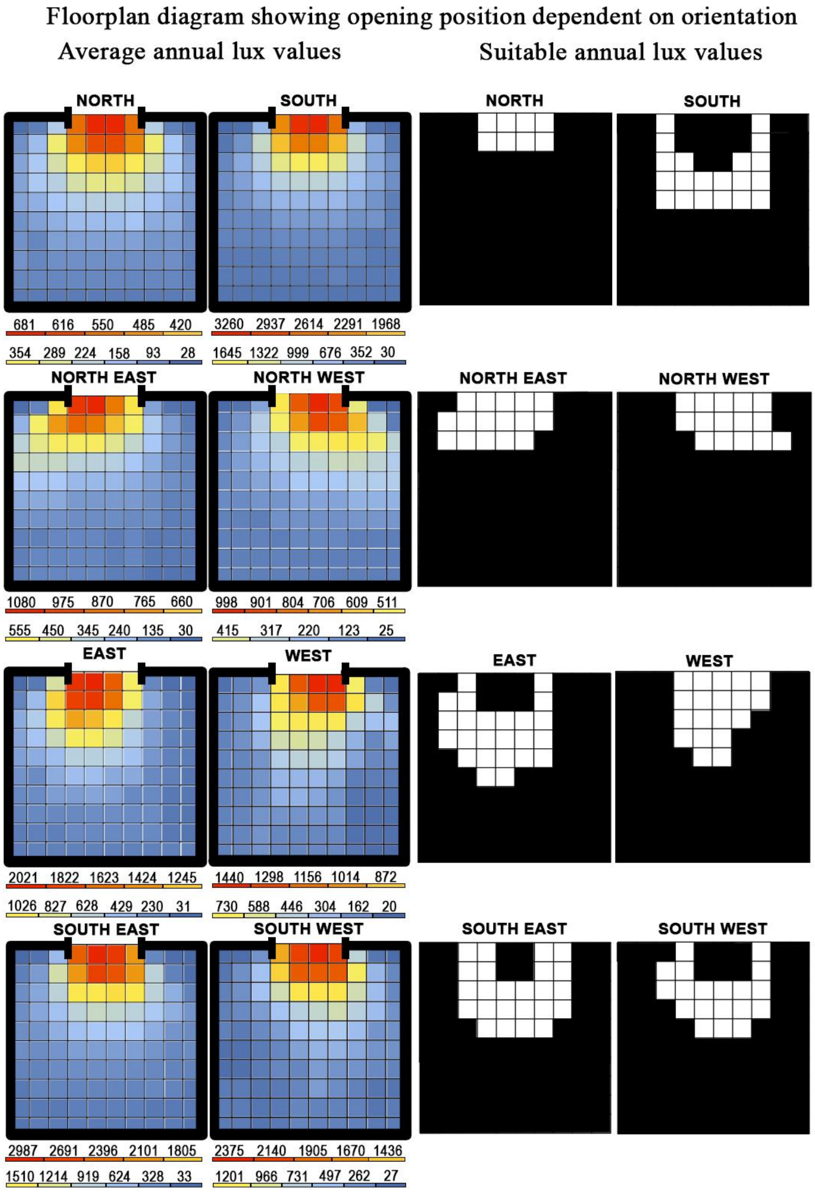

Fig. 4 Diagram analysis for lux values of light penetration throughout the whole year

4.3. Working principle

The workflow employed in this study seamlessly integrates Rhinoceros, Grasshopper, and Honeybee, with Radiance plugins, to comprehensively analyze the impact of natural daylight on interior spaces. The initial phase involves the preparation of input data, encompassing geometry and the definition of residential units and apertures. Subsequently, meteorological data and aperture orientation are considered, setting the foundation for the subsequent analyzes. Within Rhinoceros, the parameters of residential units and apertures are meticulously defined, establishing the geometrical and structural basis for the study. Transitioning to Grasshopper, the workflow incorporates building orientation analysis with specific time and date inputs. This phase is pivotal in understanding how the orientation of the building influences natural daylight exposure under varying solar conditions. The utilization of Ladybug, an environmental plugin for Grasshopper, facilitates annual daylight analysis with averaged calculation values. Ladybug employs Radiance, powerful lighting simulation software, to simulate the propagation of light within the given environment. The analysis generates a heatmap depicting lux values across the interior space, providing a visual representation of the distribution of natural daylight. The annual analysis extends the investigation from specific time and date inputs to a comprehensive evaluation of daylight conditions throughout the entire year. This is achieved through Ladybug's functionality, which calculates percentage values corresponding to the duration of specific lux ranges, creating a map that highlights the variability of natural daylight exposure over an annual cycle. In summary, the integrated workflow employs Rhinoceros, Grasshopper, and Honeybee, leveraging their capabilities to analyze the interplay between building orientation, apertures, and natural daylight (Habibi, 2022). End result is providing valuable insights into the dynamics of natural light within interior spaces. This workflow is illustrated in Figure 5, which depicts the flow method between the different software used in the study.

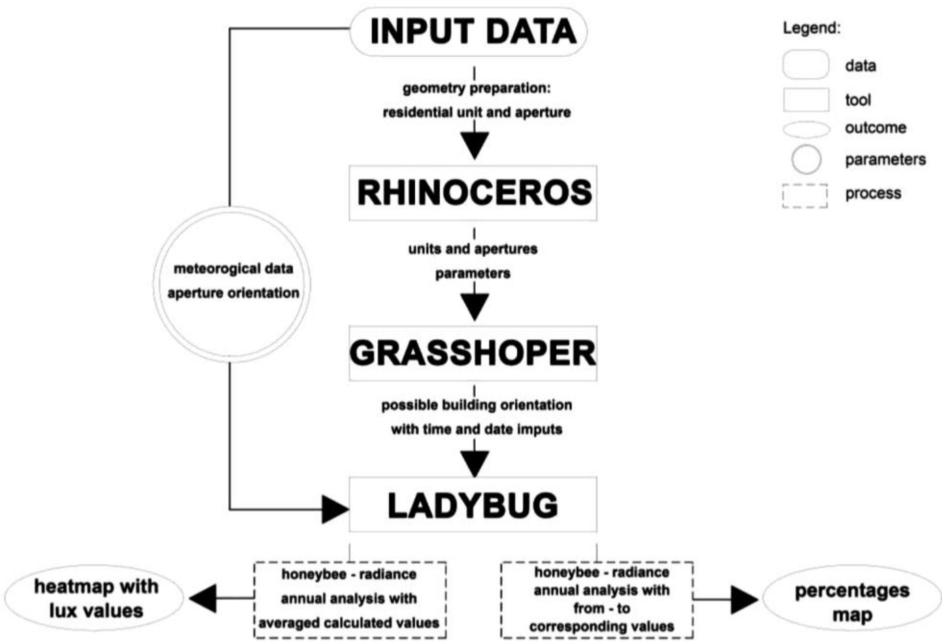

Fig. 5 The flow method between the different software

5. Discussion

The research could provide significant understanding and guidance for professionals dealing within this multidisciplinary workspace, while also presenting opportunities for additional exploration.

The incorporation of green zones within residential areas offers promising solutions to address environmental challenges and improve urban living conditions. These initiatives replenish depleted natural soil and introduce greenery into built environments, promoting sustainability and resilience in urban landscapes. Furthermore, there is a direct relationship between plot utilization and the inclusion of green spaces, where higher plot coverage necessitates allocating more square meters for greenery within residential units.

All the previously explored variables which were implemented into the optimal space were the base point for extracting data for the whole year research, and overlaying in order to get understanding of the highest percentages of positioning the plants within these spaces. The findings of the study, illustrated in Figure 6, highlight the light penetration efficiency combined for all orientations (North, South, West, East and combined), providing valuable insights into optimizing natural daylight exposure within interior spaces across various orientations. The numbers obtained present the percentages of all 8 orientations and its adequate lux number valuing from 500 to 1500 overlapped. This visualization serves as a practical guide for practitioners seeking to integrate green cores and maximize daylighting in residential environments, where in Figure 6 are shown percentages of highest valued positions within the area, and compensation with LED should be implemented in order to equalize less quality positioning, which would be mentioned detailed in the following text.

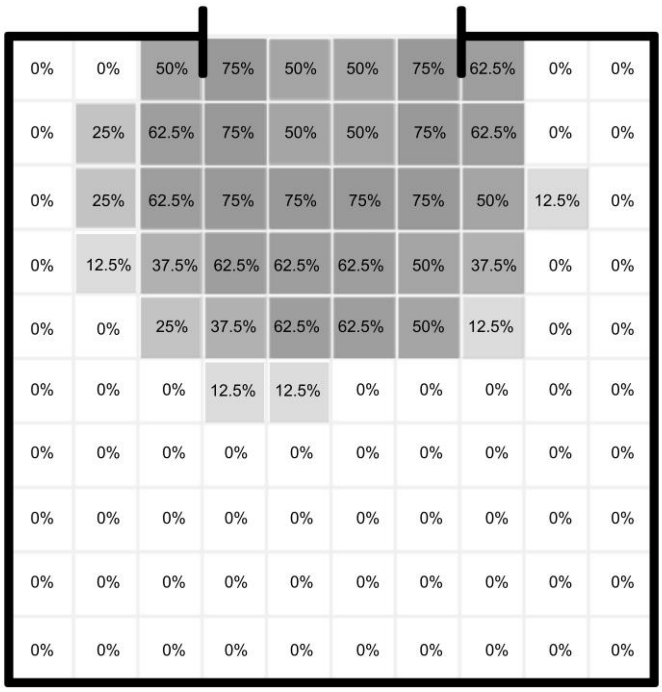

Fig. 6 Floorplan diagram for results of the most efficient positions for all orientations

As shown, finalized understanding between positions of the green cores and the environmental conditions in the built environment could be resulting in percentages of the quality light they are getting. The architectural approach to this research could benefit in understanding the interior elements and positioning. Choosing the optimal positions within the spaces could produce many multifunctional interior elements delivering dual functions – serving as a planter while utilising its architectural function.

In addition to the discussion provided, it is pertinent to address the implications of suboptimal positioning of green cores within residential units. When greenery is less adequately situated to receive requisite natural light, supplementary artificial lighting may become imperative to sustain optimal photosynthetic activity. In such scenarios, the integration of LED luminaires with tailored Photosynthetically Active Radiation (PAR) becomes indispensable to facilitate efficient photosynthesis and promote plant growth. (Ahn, et. al., 2017) LED lighting systems offer tunable spectra and intensity control, allowing for precise adjustment to meet the photosynthetic needs of plants. The deployment of intelligent lighting controls and sensor networks enables dynamic light management, optimizing energy consumption and ensuring synchronized lighting with plant growth cycles. This approach not only enhances sustainability but also augments the efficacy of indoor greening initiatives within residential contexts. The strategic deployment of LED lighting systems in conjunction with judicious placement of green cores within residential environments constitutes a comprehensive strategy for indoor greening, affording occupants the benefits of biophilic engagement while minimizing environmental footprint and maximizing energy efficiency.

Based on data from the statistical calendar of the Republic of Serbia for 2021, the construction of multi-family buildings amounted to 2310m². With an average of 4.2 residential units built per 1000 inhabitants and an average floor area of 74.86m², we can grasp the magnitude of residential development in the region. Further explanation of Table 1 is following, ratio of greenery to floor area, which represents the ratio of green spaces comparing to total area of the unit, was taken into consideration to have the lowest possible impact on the functionality of the units, but still implement the green spaces. While our study focuses on Serbia, similar trends are observed in other countries with more substantial development, underscoring the global significance of integrating green zones into residential projects. As illustrated in Table 1, the potential impact of implementing greenery within residential units can be quantified. The table provides calculations for different ratios of greenery to floor area, showing the potential average amount of greenery and total newly created greenery based on the number of residential units constructed in 2021. This data highlights the substantial contribution that integrating green spaces can make to urban environments, offering opportunities to increase green spaces annually and establish micro-ecosystems within urban environments.

Table 2 Potential greenery calculation which could be implemented

Newly build residential units in 2021.	Average floor area of residential units in 2021.	Ratio of potential amount of greenery to average floor area of units in 2021.	Potential amount of greenery applied	Potential total newly created greenery
2310 units	74.86(m^2)	1.33(%)	1(m^2)	2310(m^2)
2310 units	74.86(m^2)	2.67(%)	2(m^2)	6420(m^2)
2310 units	74.86(m^2)	6.68(%)	5(m^2)	11550(m^2)
2310 units	74.86(m^2)	9.35(%)	7(m^2)	16170(m^2)

The scope of this research is currently limited to residential buildings due to specific design considerations and regulatory contexts inherent to residential projects. Residential buildings are chosen as the least represented in biophilic practices, primarily because plant implementation in these settings raises questions of maintenance, payment, and other logistical aspects. These issues are not as prevalent in single-family housing, where homeowners typically manage plant care themselves, or in public buildings, where financial resources for maintenance can be more clearly allocated and managed, either through outsourcing or in-house teams. This context highlights why the integration of Plant Microbial Fuel Cells (PMFCs) is particularly relevant. Implementing PMFCs within residential buildings provides a sustainable energy source that can support plant maintenance, health, and other automated systems. This reduces the dependency on human intervention for plant care, ensuring that the natural components are well-maintained without imposing additional burdens on residents. The energy generated from PMFCs can possibly further automate irrigation, lighting, and climate control systems, enhancing the viability and sustainability of biophilic design in residential environments, which could represent the future investigations. While the focus is on residential buildings due to these specific challenges, this does not preclude the applicability of the findings to other building types. Future studies could explore the adaptation of green cores and PMFC technology in commercial or mixed-use buildings, potentially expanding the impact of this research. Additionally, the geographic specificity of this study, based on data from Serbia, reflects regional climate conditions, construction practices, and urban planning norms. While these findings are relevant to similar climates and contexts, further research is required to validate and adapt these principles across diverse geographic and climatic conditions to ensure broader applicability and effectiveness. In summary, the proposed design approach offers opportunities to increase green spaces annually and establish micro-ecosystems within urban environments. Through the exclusive incorporation of green zone structures, this approach aims to mitigate environmental degradation while enhancing the overall quality and sustainability of urban communities.

6. CONCLUSIONS

The conclusion of this research significantly advances our understanding of sustainable architectural design by introducing concepts such as green cores within structures and optimized lighting schemes. If flexibility in housing is to achieve its full potential, it has to mean more than endless change without fixed determinants. (Zeković, et al., 2023) Through meticulous investigation and experimentation, the study responds to pressing challenges in contemporary architecture, addressing issues related to environmental sustainability, indoor air quality, and the well-being of inhabitants. In tackling the high need for sustainable urban development, the study aligns with current global challenges, especially in the context of rapid urbanization and climate change. As cities expand and face increased environmental stress, the integration of green cores emerges as a promising solution to enhance the resilience of urban ecosystems. By strategically placing greenery within architectural designs, the research contributes to creating eco-friendly urban spaces, supporting the development of sustainable infrastructure, and mitigating the urban heat island effect. The study's emphasis on optimizing lighting schemes reflects a growing concern for energy-efficient building practices. In the face of rising energy consumption and its environmental impact, the research provides insights into designing buildings that leverage natural light effectively. Theoretical frameworks, such as the introduction of Building's Metabolism concept as the greenery being the essence of the holistic construction, elevates the study's significance by framing the integration of green cores beyond a technological standpoint.

While the research provides valuable insights and guidelines for architects and urban planners, it also opens avenues for further investigation.

Future research could delve deeper into the specific plant species best suited for green cores, exploring their ecological impact and potential benefits for air purification, and possible energy generation standpoints. Furthermore, the integration of Plant Microbial Fuel Cells (PMFCs) within green cores presents a promising area for future research. Investigating the possibilities of advanced performance and optimization of PMFCs within architectural contexts can lead to innovative solutions for sustainable energy generation within residential units. Research efforts may focus on enhancing PMFC efficiency, exploring novel electrode materials, and assessing the integration of PMFC technology with existing building systems, exploiting the existing water and electricity structures.

This research not only contributes to the current discourse on sustainable architecture but also serves as a catalyst for future investigations into biophilic design practices. By addressing contemporary challenges, proposing innovative solutions, and highlighting avenues for further research, this study offers a holistic and forward-thinking approach to shaping the future of architectural design. Moreover, the culmination of this research unveils potential avenues for future investigations, offering fertile ground for advancing our understanding of sustainable architectural design. In essence, the conclusion of this research not only marks a milestone in sustainable architectural design but also sets the stage for a plethora of future investigations, each poised to enrich our understanding and practice of integrating nature within the built environment.

REFERENCES

1. A. M. Memari, P. H. Huelman, L. D. Iulo, J. Laquatra, C. Martin, A. McCoy, I. Nahmens, and T. Williamson, Residential building construction: State-of-the-art review. Journal of Architectural Engineering, 20(4), B4014005, 2014.
2. A. Siniscalco, New frontiers for design of interior lighting products. Springer, 2021.
3. A. Trivellini, S. Toscano, D. Romano and A. Ferrante, "LED lighting to produce high-quality ornamental plants", Plants, 12(8), 1667, 2023.
4. A. Yong Deok, B. Sungwoo and K. Suk-Ju, "Power controllable LED system with increased energy efficiency using multi-sensors for plant cultivation. Energies", 2017, 10.10: 1607.
5. Biological Control of Invasive Plants in the Eastern United States. 2002. U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team.
6. Binggeli, C. Interior Graphic Standards (Vol. 21). John Wiley & Sons, 2011.
7. B. L. Ong, "Green plot ratio: an ecological measure for architecture and urban planning", Landscape and Urban Planning, 63(4), 197-211. https://doi.org/10.1016/S0169-2046(02)00191-3, 2003.
8. C. L. Jensen, "Understanding energy efficient lighting as an outcome of dynamics of social practices", Journal of Cleaner Production 165: 1097-1106, 201.7, 2017.
9. D. French, L. J. Kotzé, eds. Sustainable development goals: Law, theory and implementation. Edward Elgar Publishing, 2018.
10. H. Poorter, K. J. Niklas, P. B. Reich, J. Oleksyn, P. Poot & L. Mommer, Biomass allocation to leaves, stems and roots: meta-analyses of interspecific variation and environmental control. New Phytologist, 193(1), 30-50, 2012.
11. IEA, 2018. World Energy Outlook, 2018. IEA, Paris. Available at: https://www.iea.org/reports/world-energy-outlook-2018. License: CC BY 4.0.
12. I. Mazzoleni, Architecture follows nature-biomimetic principles for innovative design, Crc Press, 2013.

13. J. B. Foster, The vulnerable planet: A short economic history of the environment. nyu Press, 1999.
14. J. Charytonowicz, "Advances in human factors and sustainable infrastructure". In Proceedings of the 5th AHFE Conference, pp. 19-23, July 2014.
15. J. Flagler, R. P. Poincelot, People-plant relationships: Setting research priorities. New York: Food Products Press, 1994.
16. J. Qin, C. Sun, X. Zhou, H. Leng, & Z. Lian, The effect of indoor plants on human comfort. Indoor and Built Environment, 23(5), 709-723, 2014.
17. J. Yang, J. Song, & B. R. Jeong, Lighting from top and side enhances photosynthesis and plant performance by improving light usage efficiency. International Journal of Molecular Sciences, 23(5), 2448, 2022
18. M. Pavao-Zuckerman, F. R. Adler and C. J. Tanner: Urban Ecosystems: Ecological Principles for the Built Environment. Landscape Ecology. 30. 10.1007/s10980-015-0186-4, 2015.
19. R. A. Slattery and D. R. Ort, "Photosynthesis: photosynthetic efficiency improvement." Encyclopedia of Biological Chemistry III: 256-267. 2021.
20. R. J. Bula, R. C. Morrow, T. W. Tibbitts, D. J. Barta, R. W. Ignatius and T. S. Martin, "Light-emitting diodes as a radiation source for plants", HortScience, 26(2), 203–205. doi:10.21273/HORTSCI.26.2.203, 1991.
21. S. Habibi, Building Automation and Digital Technologies. Woodhead Publishing, 2022.
22. S. R. Kellert, Building for life: Designing and understanding the human-nature connection, Island press, 2012.
23. S. R. Kellert, Nature by Design: The Practice of Biophilic Design. SAD: Yale University Press, 2018.
24. S. Zeković, I. Maraš. M. Krklješ, "Exploring function adaptability and flexibility in architecture: Case study of a housing vertical", in Facta universitatis - series: Architecture and Civil Engineering 2023 Volume 21, Issue 3, Pages: 415-429, 2023.
25. UN, 2015. Transforming Our World: The 2030 Agenda for Sustainable Development. Resolution Adopted by the General Assembly on 25 September 2015, 42809, 1-13.
26. U. T. Karslı, "Integrating sustainability in interior design studio", Procedia-Social and Behavioral Sciences 106: 1532-1539, 2013.
27. V. T. Eviner, C. V. Hawkes, "Embracing variability in the application of plant–soil interactions to the restoration of communities and ecosystems", Restoration Ecology, 16(4), 713-729, 2008.
28. W. Zhong, T. Schroeder, and J. Bekkering, "Designing with nature: Advancing three-dimensional green spaces in architecture through frameworks for biophilic design and sustainability", Frontiers of Architectural Research 12.4: 732-753, 2023.
29. Y.D Ahn, S. Bae, S.-J. Kang, "Power Controllable LED System with Increased Energy Efficiency Using Multi-Sensors for Plant Cultivation", Energies 2017, 10, 1607. https://doi.org/10.3390/en10101607

POZICIONIRANJE ZELENIH JEZGARA ZA GENERISANJE ELEKTRIČNE ENERGIJE U STAMBENIM JEDINICAMA

Ova studija istražuje metodološki pristup arhitektonskom dizajnu uvodeći koncept zelenih jezgara, istovremeno optimizujući osvetljenje u stambenoj arhitekturi kako bi se podstakao simbiotički odnos između prirode i građenog okruženja. Razmatra se kompleksno međusobno delovanje dinamike svetla i ekoloških varijabli koje su ključne za efikasnu proizvodnju energije i rast biljaka. Istraživanje ima za cilj da istražuje unutrašnje prostore kao dinamične ekosisteme koji podstiču ekološku održivost kako bi se omogućilo ljudsko stanovanje u urbanim ekosistemima, rezultirajući u prezentovanju optimalnih pozicija zelenila zarad holističkog pristupa. Shvatajući naučne principe iza ove integracije prirode i tehnologije, ovo istraživanje ima za cilj da razume temelje za biofilne prakse u savremenoj arhitekturi. Osim toga, ovo istraživanje služi kao preteča daljim istraživanjima o ćelijskim gorivima biljaka u arhitektonskom projektovanju. Istraživanje je razvijeno kroz pristup istraživanja kroz dizajn, koristeći metod dijagrama radi određivanja optimalnih uslova.

Ključne reči: *prostorno strukturisanje, dinamika svetla, ekološke varijable, urbanistički ekosistemi, integracija prirode, ćelijska goriva biljaka*