Issue No. 1 · 2026
ADVANCED STUDIES
IN ARCHITECTURE AND CIVIL ENGINEERING
(ASACE)

ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

UDC 72.01
Review article

CC BY 4.0

EVOLUTION OF SUSTAINABLE ARCHITECTURE IN THE 21ST CENTURY: TYPOLOGY OF ADAPTIVE BUILDINGS

Y. Onichshenko[1]*, G. Abdrassilova[1], A.Ujma[2]

[1]International Educational Corporation, 050043, Almaty, Kazakhstan
[2]University of Applied Sciences in Nysa, 448-300, Nysa, Poland

*Corresponding author, e-mail: iu.onishchenko@kazgasa.kz

ABSTRACT

Introduction. The concept of sustainable development in the 21st century defines one of the key directions of contemporary architectural design, integrating the requirements of energy efficiency, environmental safety, and the adaptability of buildings to changing environmental conditions. This article examines the formation of sustainable architecture in the context of global contemporary challenges, including the energy crisis, increasing carbon dioxide emissions, urbanization processes, and intensifying climate change. **Materials and Methods.** The methodological basis of the study is a comparative analysis of implemented architectural projects and the systematization of contemporary approaches to sustainable design. International and national case studies were examined, including the Bullitt Center, Passive House, The Edge, Bosco Verticale, Park 20|20, and Talan Towers, to identify the principal architectural approaches and technologies associated with sustainable development. **Results and Discussion.** The analysis demonstrates that sustainable architecture has evolved from isolated energy-saving solutions toward integrated sustainable systems and buildings with zero or minimal energy consumption. Based on the examined projects, several building types were identified within the framework of sustainable development, including energy-efficient, passive, bioclimatic, intelligent ("smart"), healthy, life-supporting, green, circular, and functionally flexible buildings. The investigated examples illustrate the practical application of these approaches in different climatic, technological, and socio-economic contexts. The findings also reveal the growing importance of adaptability as a design principle that enhances environmental performance, functional resilience, and the long-term sustainability of the built environment. **Conclusions.** The study concludes that adaptive architecture represents an integral component of sustainable development. A typological model consisting of nine groups of buildings is proposed, reflecting the evolution of sustainable architecture from energy-efficient solutions to zero-energy and regenerative architectural systems.

KEYWORDS: sustainable architecture; energy efficiency; adaptive buildings; passive house; smart buildings; green buildings; circular architecture.

FOR CITATION:

Onichshenko Y., Abdrassilova G., Ujma A. Evolution of sustainable architecture in the 21st century: typology of adaptive buildings. Advanced Studies in Architecture and Civil Engineering. 2026; 1 (1): 26-35.

© Onichshenko Y., Abdrassilova G., Ujma A., 2026

Issue No. 1 · 2026
ADVANCED STUDIES
IN ARCHITECTURE AND CIVIL ENGINEERING
(ASACE)
ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

1 INTRODUCTION

The problem of sustainability of material structures has gained global recognition and was formalized in the Sustainable Development Agenda adopted by the United Nations General Assembly in 2015. The program includes 17 goals aimed at improving the quality of life and protecting the planet. Of particular relevance for architecture is Goal 11 - Sustainable Cities and Communities, which directly links the safety and quality of the urban environment with the sustainability of architectural and urban planning solutions. Within the framework of this goal, architecture is considered one of the key instruments for the formation of sustainable urban systems [1].

A turning point in the transformation of perspectives on global environmental security was the energy crisis of the 1970s, after which the concept of energy-efficient design began to develop in architecture. During this period, issues related to the thermal efficiency of buildings, rational energy use, and the optimization of engineering systems became particularly important. At the same time, rapid urbanization, increasing carbon dioxide emissions, ecosystem degradation, and climate change intensified the need for environmentally responsible architectural solutions [2]. Contemporary architecture is therefore increasingly viewed as an adaptive system capable of responding to environmental, technological, and social challenges.

Despite the significant number of studies devoted to energy efficiency and ecological construction, sustainable architectural solutions are often examined separately within specific research directions, including passive houses, green buildings, intelligent building management systems, and circular construction [1,3,4]. Previous studies have extensively investigated energy-saving technologies, sustainable materials, environmental certification systems, and building performance optimization [5-9].

However, a comprehensive typology that reflects the interrelationships among different sustainable architectural approaches and their evolutionary development remains insufficiently explored [10,11]. Existing research generally focuses on individual concepts rather than considering sustainable architecture as an integrated system of interconnected principles, technologies, and adaptive strategies. In this regard, the systematic analysis of implemented projects and the identification of common adaptive characteristics become particularly relevant [12].

The aim of this study is to identify the main directions in the formation of sustainable architecture in the 21st century and to develop a typological classification of adaptive architectural solutions based on the analysis of implemented projects. The scientific novelty of the research lies in the systematization of contemporary directions of sustainable architecture and the development of a typological model comprising nine groups of buildings, reflecting the evolution of sustainable architecture from energy-efficient solutions to regenerative architectural systems.

2 METHODS AND MATERIALS

This article is conducted as a review study aimed at identifying patterns in the formation of sustainable architecture and systematizing contemporary architectural solutions within the framework of the sustainable development concept [1]. The methodological basis of the research is a comprehensive analysis of implemented architectural projects representing various directions of sustainable design.

During the study, a comparative analysis method was applied, allowing the architectural, technological, and environmental characteristics of prominent sustainable architecture projects implemented in different countries to be compared [3]. The comparison was carried out based on several criteria, including the level of energy efficiency, the use of renewable energy sources, the integration of natural processes

ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

into the architectural structure, the application of digital building management systems, and the degree of resource autonomy of buildings.
An important stage of the research was the systematization of architectural techniques and engineering solutions used in sustainable buildings. The analysis included such elements as natural ventilation and daylighting systems, the use of solar energy, green roofs and façades, heat recovery technologies, water collection and reuse systems, as well as intelligent building management systems [6].
Based on the identified characteristics, buildings were typologized according to their adaptive qualities within the structure of sustainable development. The main criterion for typologization was the dominant architectural and technological principles that determine the environmental efficiency of buildings and their ability to adapt to changing environmental and operational conditions [10].
The final stage of the research consisted of an analytical generalization of the identified architectural trends, which made it possible to trace the evolution of architectural approaches - from energy-efficient buildings of the second half of the 20th century to contemporary models of zero-energy, life-supporting, and regenerative architectural systems [11]. This approach allowed the formation of a typological model of adaptive architectural solutions within the framework of sustainable development reinforced foundation; E_u - is the modulus of elasticity of the non-reinforced foundation.

3 RESULTS AND DISCUSSION

Global architectural practice in recent decades demonstrates a stable trend toward the integration of sustainable development principles into building design. The analysis of implemented projects makes it possible to identify a wide range of architectural and engineering solutions aimed at reducing energy consumption, minimizing environmental impact, and improving indoor environmental quality. The examined examples of sustainable architecture of the 21st century reflect different ways of implementing these principles - from energy efficiency and bioclimatic strategies to the integration of digital technologies and circular economy approaches [1,8]. One of the most widely recognized examples of sustainable architecture is the Bullitt Center office building, constructed in Seattle (USA) in 2013 and designed by the Miller Hull Partnership. This project is considered one of the most prominent examples of buildings with net-zero energy consumption and a high degree of resource autonomy. The six-storey office building with an area of approximately 4,650 mZ demonstrates the comprehensive application of environmentally oriented technologies. The project incorporates a rainwater harvesting system that collects water in tanks with a capacity of more than 250,000 liters, followed by filtration and reuse for technical purposes. A distinctive feature of the building is the use of composting toilets and the exclusion of more than 350 commonly used toxic chemical substances, including PVC, lead, mercury, phthalates, and formaldehyde [10]. The building's energy supply is provided by photovoltaic panels installed on the roof, which generate approximately 230,000 kWh of electricity per year. The concept of the Bullitt Center is based on the idea of "living architecture" , implying the autonomous functioning of the building through the use of natural resources. The architectural form is oriented toward maximizing natural daylight and ventilation. Large-scale glazing, the use of heat pumps, and highly efficient ventilation and heat-exchange systems ensure a comfortable indoor climate with minimal energy consumption for heating and cooling. In this way, the Bullitt Center demonstrates a transition from energy efficiency as a partial objective toward a model of a resource-autonomous building.

A fundamental stage in the development of sustainable architecture was the concept of the Passive House, first implemented in Darmstadt (Germany) in 1993 under the

ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

leadership of German engineer Wolfgang Feist. The passive house represents a building that practically does not require conventional heating systems due to the use of passive energy sources. The main principle of this concept lies in maximizing solar gains and internal heat gains generated by household appliances and human activity while minimizing heat losses through the building envelope [5]. Key characteristics of passive houses include highly efficient thermal insulation of walls, roofs, and floors, triple-glazed windows, exceptional airtightness of the building envelope, and mechanical ventilation systems with heat recovery. Heat recovery allows the extraction of heat from exhaust air and its transfer to incoming fresh air, significantly reducing the need for additional heating. Architectural solutions also consider the orientation of buildings relative to the sun in order to maximize solar heat gain in winter and prevent overheating in summer. Compared with conventional buildings, passive houses consume 80-90% less energy for heating and cooling. Therefore, this approach can be considered the fundamental "energy level" of sustainable architecture upon which more complex ecological and digital strategies are subsequently developed [3].

The transition from purely thermal optimization toward interaction with natural processes is demonstrated by the Center for Sustainable Development designed by William McDonough and his architectural firm William McDonough + Partners and built in Charlottesville (USA) in 2006. The building represents an example of bioclimatic architecture based on the use of natural environmental factors to maintain comfortable indoor conditions. The architectural concept includes natural ventilation achieved through proper building orientation and spatial organization.

Large windows and light wells ensure the maximum use of daylight, thereby reducing the demand for artificial lighting. Solar panels installed on the roof provide renewable energy, while a rainwater harvesting system is used for technical purposes. The project also incorporates elements of biophilic design: the integration of green spaces inside and around the building contributes to improved microclimatic conditions, better air quality, and the creation of a comfortable environment for users. Green roofs and façades additionally function as thermal insulation and help mitigate the urban heat island effect. Thus, the bioclimatic approach expands the framework of sustainability by complementing energy efficiency with ecological and spatial-environmental mechanisms [7].

Further development of sustainable architecture is associated with the integration of digital technologies and intelligent building management systems, which increase the adaptability of buildings during operation. An example of this direction is The Edge office building in Amsterdam (2014), designed by PLP Architecture. The building is considered one of the most "intelligent" buildings in the world due to its advanced management system based on a network of sensors and Internet of Things (IoT) technologies that monitor lighting levels, temperature, humidity, and occupancy in real time [6].

The collected data are used to automatically regulate lighting, heating, and ventilation systems. An innovative feature is the use of Philips LED lighting panels operating via Power-over-Ethernet technology, which reduces energy consumption and enables flexible lighting control. Solar panels installed on the roof and façades generate a significant portion of the energy required for building operation. The central atrium increases the use of natural daylight, while user control of the indoor microclimate through a mobile application enhances comfort and spatial flexibility. As a result, "smart architecture" represents the next level of sustainability - the ability of buildings to dynamically adapt to changing environmental conditions and operational scenarios.

Parallel to digitalization, another direction has developed that focuses on the ecological integration of natural components

ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

into building structures, where greenery is considered not as decoration but as a functional element of sustainability. The residential complex One Central Park in Sydney (2013), designed by Jean Nouvel, is often interpreted as an example of a "healthy building," where architecture and natural elements are integrated to create a favorable living environment. The main feature of the complex is its vertical gardens developed by botanist Patrick Blanc: more than 50,000 plants of various species are integrated into the façades, improving air quality, reducing pollution, and creating a comfortable microclimate [12]. An additional architectural element is the heliostat system, which redirects sunlight to shaded areas of the complex and surrounding spaces. The building also uses rainwater collection and recycling systems for irrigation and technical needs. A similar technological approach but with a different ecological effect is demonstrated by Bosco Verticale ("Vertical Forest") in Milan (2014), designed by Stefano Boeri. The façades of the two residential towers, 80 and 112 meters high, incorporate more than 900 trees, around 5,000 shrubs, and 11,000 plants. This façade greenery contributes to the filtration of air pollutants, the reduction of urban temperatures, and the formation of an urban ecosystem supporting biodiversity. While One Central Park emphasizes the health and comfort of the indoor environment, Bosco Verticaledemonstrates the potential of buildings as components of urban ecological infrastructure.

The concept of buildings aimed at minimizing environmental impact across the entire life cycle and achieving high standards of ecological performance is illustrated by The Crystal in London (2012), designed by WilkinsonEyre [8]. The building functions as a demonstration center for sustainable urban development and green construction technologies. It incorporates solar panels, heat pumps, intelligent energy management systems, and rainwater harvesting systems. The application of energy-efficient technologies and sustainable materials enabled the building to achieve the highest international environmental certification levels - LEED Platinum and BREEAM Outstanding - making it an example of an institutionally validated model of sustainable architecture.

The development of sustainable architecture toward resource circularity is reinforced by concepts of circular construction based on the principles of the circular economy. The Park 20|20 project in the Netherlands (2012) is one of the first commercial complexes fully designed according to circular principles: building materials are intended for reuse and recycling at the end of the building's life cycle. The project incorporates renewable energy sources, rainwater harvesting systems, green roofs and façades, and design solutions that provide natural ventilation and maximize daylight use. Thus, the circular approach expands the concept of sustainability into the domain of controlled material cycles [8].

In the context of architectural practice in Kazakhstan, the multifunctional complex Talan Towers in Astana (2018), designed by the SOM architectural bureau, is particularly illustrative. The complex includes office spaces, the Ritz-Carlton hotel, residential apartments, and commercial areas. The architectural concept is oriented toward functional flexibility and the possibility of transforming interior spaces according to user needs. The building is equipped with intelligent building management systems (BMS) that control microclimate, lighting, and security. Energy-efficient solutions are implemented, including natural daylighting, modern ventilation systems, and energy-efficient materials. The complex has received LEED Gold certification. This example confirms the relevance of sustainable and adaptive architecture for the Kazakhstani context, where both energy efficiency and flexibility of building use scenarios are important [14,15], (Fig. 1)

Issue No. 1 · 2026
ADVANCED STUDIES
IN ARCHITECTURE AND CIVIL ENGINEERING
(ASACE)
ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

Building, Country, Year	Object Photo	Architectural Type	Key Sustainable Technologies
Bullitt Center, USA, 2013		Zero-energy building	Solar panels, rainwater harvesting, composting toilets, natural ventilation
Passive House (Darmstadt), Germany, 1993		Passive building	Superinsulation, airtight envelope, heat recovery ventilation
Center for Sustainable Development USA, 2006		Bioclimatic architecture	Natural ventilation, daylighting, green roofs, rainwater harvesting
The Edge, Netherlands, 2014		Smart building	IoT sensors, automated climate control, digital building management
One Central Park, Australia, 2013		Healthy building	Vertical gardens, heliostat system, rainwater reuse
Bosco Verticale, Italy, 2014		Green building	Vertical vegetation, biodiversity integration
The Crystal, United Kingdom, 2012		Life-supporting building	Solar energy, heat pumps, smart energy systems
Park 20|20, Netherlands, 2012		Circular building	Reusable materials, circular design, renewable energy systems
Talan Towers, Kazakhstan, 2018		Functionally flexible building	Modular spaces, BMS systems, energy-efficient design

Fig. 1. Typology of adaptive buildings in sustainable architecture (based on analyzed case studies)

A comparison of the presented projects reveals a consistent evolution of architectural solutions within the framework of sustainable development: from the optimization of physical building characteristics (energy-efficient and passive models) to the integration of natural processes (bioclimatic architecture), followed by digital control (intelligent buildings), ecological integration (green infrastructure), resource autonomy and institutional sustainability standards (zero-energy and certified buildings), and finally circularity and functional flexibility as responses to changing socio-economic conditions (Fig. 2).

Thus, the analyzed examples make it possible to identify several interconnected directions in the development of contemporary sustainable architecture: energy-efficient and passive architecture; bioclimatic architecture; intelligent (smart) architecture; ecologically integrated architecture; life-supporting buildings; circular architecture; and functionally flexible buildings.

These directions do not exist in

ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

isolation; rather, they form an integrated system of architectural solutions united by the common goal of minimizing environmental impact and increasing the sustainability of the built environment. As a result, a new architectural paradigm is emerging in which a building is considered an adaptive system interacting with natural environments, technological infrastructures, and social needs.

Based on comparative analysis, adaptive solutions can be grouped into nine typological categories:

1. Energy-efficient buildings with zero or minimal consumption of energy from conventional sources;

2. Passive buildings (superinsulation, heat recovery, and the absence of conventional heating systems);

3. Bioclimatic architecture (use of natural processes to form indoor microclimate);

4. Smart architecture (digital control of building systems);

5. Healthy buildings (ecologically safe indoor environment and comfort);

6.Life-supporting buildings with zero environmental indicators (resource autonomy, recycling, and energy generation);

7. Green buildings (vegetation integration, local materials, and reduction of carbon footprint);

8. Circular buildings (closed material cycles, repairability, and reuse of building components);

9. Functionally flexible buildings (modular design and adaptability to future scenarios). It should be emphasized that these categories are not rigidly isolated. In real architectural practice, different characteristics often overlap - for example, green buildings may simultaneously be energy-efficient and smart, while circular solutions may coexist with functional flexibility. Nevertheless, the proposed typology reflects the dominant adaptive qualities of buildings and illustrates the general trajectory of architectural development - from energy-efficient solutions of the late 20th century toward zero-energy, resource-autonomous, and regenerative architectural models of the 21st century.

4 CONCLUSION

1. The conducted analysis demonstrates that the global energy crisis of the second half of the twentieth century, together with increasing environmental threats, became key factors in the transformation of the architectural paradigm toward the principles of sustainable development. The awareness of the limited nature of natural resources and the negative environmental impact of the construction industry led to the emergence of new approaches to building design aimed at reducing energy consumption, minimizing emissions, and ensuring the rational use of resources.

2. Architecture of the 21st century demonstrates a gradual transition from isolated energy-saving solutions to a comprehensive model of sustainability that integrates energy efficiency, environmentally friendly construction materials, the use of renewable energy sources, digital control of engineering systems, water efficiency, integration of natural elements, and the principles of the circular economy. Modern buildings are increasingly considered not only as engineering structures but also as components of ecological and technological systems within the urban environment.

3. Based on a comparative analysis of implemented projects, a typology of adaptive architectural solutions is proposed, including nine groups: energy-efficient buildings, passive buildings, bioclimatic architecture, smart architecture, healthy buildings, life-supporting buildings with zero environmental indicators, green buildings, circular buildings, and functionally flexible buildings. This classification makes it possible to systematize contemporary directions of sustainable architecture and may serve as a methodological basis for further scientific research as well as for the development of

ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

educational modules in architectural design.

4. Adaptive architecture represents an important component of the sustainable development concept, as it ensures the ability of buildings to respond to changing climatic, technological, and socio-economic conditions. The integration of adaptive solutions contributes to improving the environmental efficiency of buildings, reducing operational costs, and creating a more comfortable and healthy environment for people.

5. Overall, the results of the study confirm that the development of sustainable architecture in the 21st century is associated with the formation of a new architectural paradigm in which buildings are considered dynamic systems capable of interacting with the natural environment, technological infrastructure, and societal needs. This approach defines a promising direction for the development of architectural design and urban planning in the context of global environmental and climate changes.

REFERENCES

1. Zuo J., Zhao Z. Green Building Research – Current Status and Future Agenda: A Review. Renewable and Sustainable Energy Reviews. 2014;30:271–281. 10.1016/j.rser.2013.10.021

2. Urenev V., Bakhtin D. Creation Principles of Sustainable Public Architecture Building on the World Practice Example [Principy sozdaniya ustoichivoi arhitectury obshestvennyh zdanii na primere mirovoi praktiki]. Problems of Theory and History of Architecture of Ukraine. 2020;20:8-18. 10.31650/2519-4208-2020-20-8-18 (in Russ.)

3. Mitchell I.K., Walinga J., The creative imperative: The role of creativity, creative problem solving and insight as key drivers for sustainability. Journal of Cleaner Production. 2017;141:115 – 125. 10.1016/j.jclepro.2016.09.162

4. Bhandari D. Architecture and Green Building Practices: A Perspective of Sustainable Development. Journal of UTEC Engineering Management. 2025;3(1):27–36. 10.3126/juem.v3i1.84815

5. Cabeza L.F., Barreneche C., Miró L., Morera J.M., Bartolí E., Fernández A.I. Low Carbon and Low Embodied Energy Materials in Buildings: A Review. Renewable and Sustainable Energy Reviews. 2013;23:536–542. 10.1016/j.rser.2013.03.017

6. Dwaikat L., Ali K. Green Buildings Life Cycle Cost Analysis and Life Cycle Budget Development: Practical Applications. Journal of Building Engineering. 2016;5:72–77. 10.1016/j.jobe.2015.11.008

7. Lehmann S. Low Carbon Construction Systems Using Prefabricated Engineered Solid Wood Panels for Urban Infill to Significantly Reduce Greenhouse Gas Emissions. Sustainable Cities and Society. 2013;6:57–67. 10.1016/j.scs.2012.08.004

8. Pomponi F., Moncaster A. Circular Economy for the Built Environment: A Research Framework. Journal of Cleaner Production. 2017;143:710–718. 10.1016/j.jclepro.2016.12.055

9. Kibert C.J. Sustainable Construction: Green Building Design and Delivery. Journal of Green Building. 2008;11(3):1–3.

10. Cole R.J. Transitioning from Green to Regenerative Design. Building Research & Information. 2012;40(1):39–53. 10.1080/09613218.2011.610608

11. du Plessis C., Cole R.J. Motivating Change: Shifting the Paradigm. Building Research & Information. 2011;39(5):436–449. 10.1080/09613218.2011.582697

12. Triratma B., Yuliani S., Sofyan Y.E., Basith A. Adaptive Reused Heritage Building Based on Sustainable Architecture. ARTEKS: Jurnal Teknik Arsitektur. 2023;8(3):453–464. 10.30822/arteks.v8i3.2635

ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

13. Pomponi F., Moncaster A. Embodied Carbon Mitigation and Reduction in the Built Environment – What Does the Evidence Say Journal of Environmental Management. 2018;181:687–700. 10.1016/j.jenvman.2016.08.036

14. Abdrassilova G.S., Danibekova-Murzagaliyeva E. Accessibility as a Criterion of Quality in an Architectural Spatial Environment (on the Example of the City of Almaty). Budownictwo o Zoptymalizowanym Potencjale Energetycznym. 2020;9(1):39–46. 10.17512/bozpe.2020.1.04

15. Abdrassilova G.S. , Aukhadiyeva L.M. Priority Directions for the Development of Regional Architecture in Kazakhstan in the 21st Century. Bulletin of Kazakh Leading Academy of Architecture and Construction. 2024;93(3):7–22. 10.51488/1680-080X/2024.3-01

ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ARTIFICIAL INTELLIGENCE STATEMENT

During the preparation of this manuscript, the authors used [tool name, version] solely for language editing and grammar checking. The authors reviewed and edited the output and take full responsibility for the scientific content, analyses, interpretations and conclusions of the article.

INFORMATION ABOUT THE AUTHORS

Onichshenko Yuliya Vladimirovna – PhD, Associate Professor of the School of Architecture, International Educational Corporation (KazGASA), Almaty, Kazakhstan, iu.onishchenko@kazgasa.kz, https://orcid.org/0000-0001-8749-8718
Abdrassilova Gulnar Seydukhmetovna – Doctor of Architecture, Research Professor of the School of Architecture, International Educational Corporation (KazGASA), Almaty, Kazakhstan, gulnar.abdrassilova@kazgasa.kz, https://orcid.org/0000-0002-3828-9220

AUTHORS CONTRIBUTION

Onichshenko Y.V. - research concept; literature review; analysis of international architectural practice; development of typological classification; preparation and writing of the manuscript
Abdrassilova G.S. - scientific consultation; review and editing of the manuscript

The article was submitted 18 May 2026; approved after reviewing 15 June 2026; accepted for publication 22 June 2026.