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TECHNOLOGICAL SOLUTIONS FOR ENHANCING THE RESISTANCE OF HIGH-RISE BUILDING FACADES TO ATMOSPHERIC IMPACTS

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Abstract
This article analyzes modern technological solutions aimed at improving the resistance of high-rise building facades to atmospheric impacts. The influence of environmental factors on facade materials is evaluated, and the advantages of nanocoatings, hydrophobic protective materials, ventilated facade systems, and composite materials are examined. The research findings show that the integrated application of these technologies contributes to extending facade service life, reducing maintenance costs, and improving structural durability. In addition, the priority directions for developing atmospheric-resistant facade systems are substantiated.

Keywords: High-rise buildings, facade systems, atmospheric impacts, nanocoatings, hydrophobic coatings, ventilated facades, composite materials, durability, operational efficiency, service life.

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Introduction

The construction industry is an essential component of economic development, modern urbanization, and infrastructure expansion. The construction of high-rise buildings contributes to the efficient utilization of land resources, the accommodation of residential and service facilities in accordance with contemporary requirements, and the enhancement of urban architectural appearance [10]. Therefore, ensuring the reliability, safety, and long-term operational efficiency of high-rise buildings has become one of the priority scientific and practical areas in the construction sector.

Facade systems play a particularly important role in high-rise buildings, as they not only define the architectural appearance of a structure but also serve as the primary protective barrier against adverse atmospheric influences [3]. The technical condition and service life of facades directly affect the overall operational performance of a building. Consequently, improving the resistance of facades to atmospheric impacts is closely associated with the advancement of construction materials and technologies [7].

The relevance of this topic is determined by the fact that high-rise building facades are continuously exposed to various atmospheric loads throughout their service life. Moisture, precipitation, wind pressure, ultraviolet radiation, and repeated temperature fluctuations affect the physical and mechanical properties of facade materials, accelerating their deterioration processes [19; 20]. As a result, microcracks may develop, protective layers may degrade, corrosion processes may intensify, and the operational characteristics of facade systems may decline [7; 17]. These effects ultimately increase maintenance costs and reduce the service life of facade structures.

The development of construction technologies has created new opportunities for effectively addressing these challenges. International practice demonstrates that the application of nanocoatings, hydrophobic protective materials, ventilated facade systems, high-strength composite materials, and adaptive facade technologies significantly reduces the negative impact of atmospheric factors [1; 5; 12]. These technologies improve moisture resistance, slow down corrosion processes, enhance structural stability, and extend the service life of facade systems [8; 14].

The scientific significance of this issue lies in the fact that improving facade durability cannot be achieved solely through the use of a single material or

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individual technology. The development of facades resistant to atmospheric impacts requires a balanced combination of material quality, protective coatings, structural solutions, and operating conditions [4; 13]. Therefore, the comprehensive evaluation of modern facade technologies, the identification of their advantages, and the improvement of their practical implementation mechanisms represent important scientific tasks.

International studies confirm that the application of weather-resistant facade systems contributes to reducing maintenance costs, extending the service life of building structures, and improving overall operational performance [5; 10; 14]. At the same time, selecting technologies aimed at mitigating atmospheric impacts requires a comprehensive assessment of their technical, economic, and operational effectiveness. This aspect determines both the scientific and practical significance of the present study.

Accordingly, the objective of this research is to analyze modern technological solutions aimed at enhancing the resistance of high-rise building facades to atmospheric impacts, evaluate their operational advantages, and develop scientific and practical recommendations for ensuring the long-term durability and stability of facade systems. The findings of this study will contribute to the development of weather-resistant facade systems, improve the reliability of construction facilities, and support their efficient long-term operation.

METHODOLOGY

This study investigates the effectiveness of technological solutions aimed at improving the resistance of high-rise building facades to atmospheric impacts through a comprehensive research approach. The theoretical and informational basis of the research consists of international scientific publications published between 2020 and 2025 focusing on facade material durability, protective coatings, ventilated facade systems, composite materials, and adaptive facade technologies [1–20].

The study employed comparative analysis, content analysis, synthesis, and a systems approach. Comparative analysis was used to evaluate the effects of atmospheric factors on facade materials and to assess the operational advantages of nanocoatings, hydrophobic coatings, ventilated facades, and composite materials [1; 5; 12; 19]. Through content analysis, international experiences were examined, and the key factors affecting facade service life, as well as

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technological approaches aimed at minimizing deterioration, were systematically identified [7; 14; 20].

The methodological framework of the research was based on identifying the relationships among atmospheric factors, protective technologies, and operational performance. For this purpose, facade durability was evaluated from the perspectives of the physical and mechanical properties of materials, moisture protection performance, structural design solutions, and adaptability to external environmental loads [4; 8; 17]. Based on the synthesis of the obtained results, the combined application of protective coatings, ventilated facade systems, and modern composite materials was identified as the most effective approach for improving resistance to atmospheric impacts [5; 12; 18]. This approach contributes to extending the service life of facade systems, reducing maintenance and operational costs, and ensuring the long-term durability and sustainability of construction facilities.

LITERATURE REVIEW

High-rise building facades are among the most important structural elements that ensure interaction between a building and the external environment. Their technical condition and operational reliability are largely determined by their resistance to atmospheric influences [3; 10]. In construction practice, the long-term durability of facade systems is essential not only for preserving the aesthetic appearance of buildings but also for ensuring technical safety, energy efficiency, and economic performance [7]. Therefore, the development of facade systems resistant to atmospheric impacts has become one of the key research directions in construction materials science and modern facade technologies.

Research findings indicate that moisture, ultraviolet radiation, wind loads, air pollution, and cyclic temperature variations are among the most significant factors affecting facade performance [19; 20]. In particular, moisture penetration into construction materials accelerates corrosion processes, promotes the formation of microcracks in concrete and composite materials, and reduces the mechanical strength of structural components [7; 17]. Ultraviolet radiation negatively affects the color stability and physical properties of facade materials, contributing to their accelerated deterioration [18]. Consequently, researchers emphasize the importance of improving material compositions and developing

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advanced protective technologies to minimize the adverse effects of atmospheric factors [1].

Among the technologies developed for facade protection, nanocoatings occupy a prominent position [1; 17]. Nanocoatings create an ultra-thin protective layer on material surfaces, limiting the penetration of water and aggressive chemical substances into the structure of the material [1]. According to researchers, such coatings not only provide protection against moisture but also reduce the impact of ultraviolet radiation and help preserve the aesthetic properties of materials over extended periods [9]. Furthermore, nanotechnology-based coatings enhance the self-cleaning capabilities of facades and contribute to reducing maintenance costs [17].

In addition to nanocoatings, hydrophobic protective materials are also considered an effective solution against atmospheric impacts [18]. Hydrophobic treatments prevent water droplets from penetrating facade surfaces and slow down deterioration processes associated with moisture exposure [18]. Scientific studies have shown that the application of such coatings is particularly effective in regions characterized by high levels of precipitation, where they significantly contribute to extending the service life of facade systems [7].

Improving resistance to atmospheric factors is not limited to the use of advanced materials and coatings. Recent studies recognize ventilated facade systems as an effective structural solution [5; 13]. The principle of this technology is based on creating an air cavity between the facade cladding and the primary wall structure [5]. Natural air circulation within this cavity prevents moisture accumulation, preserves the effectiveness of thermal insulation layers, and helps maintain dry structural conditions [13]. As a result, the negative effects of atmospheric influences are minimized, and the service life of facade systems is extended [5].

Research aimed at improving the composition of facade materials also plays a significant role in enhancing atmospheric resistance. Recent studies identify composite materials, fiber-cement panels, and advanced polymer-based facade claddings as materials with superior operational performance [12; 19]. Their main advantages include high mechanical strength, excellent moisture resistance, and superior corrosion resistance [12]. In addition, the relatively low weight of composite materials contributes to reducing structural loads in high-rise buildings [10].

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Adaptive and smart facade systems have emerged as a separate scientific direction in the development of facade technologies [4; 6]. These systems are capable of responding to environmental conditions and adjusting their performance according to changes in temperature, humidity, and solar radiation [6]. Researchers emphasize that such facades not only reduce the impact of atmospheric loads but also improve overall energy efficiency [4]. In this regard, adaptive facades are considered an innovative solution that combines durability with energy-saving performance [8].

An analysis of international experience indicates that the use of weather-resistant facade technologies has become an important component of construction policies in Germany, South Korea, Singapore, and other developed countries [10; 14]. The implementation of nanocoatings, ventilated facades, composite materials, and intelligent management systems in these countries has significantly extended facade service life and optimized operational costs [8; 14].

In summary, the literature review demonstrates that the resistance of facades to atmospheric impacts depends on the combined influence of material properties, protective coatings, structural solutions, and advanced technologies [5; 12; 17]. However, existing studies have not sufficiently addressed the comprehensive assessment of atmospheric resistance or provided a unified framework for comparing the effectiveness of different technological solutions. This situation highlights the need for further scientific investigation and justification of technological approaches aimed at improving the long-term operational stability of high-rise building facades [19; 20].

ANALYSIS AND RESULTS

The resistance of high-rise building facades to atmospheric impacts is one of the key factors determining the long-term operational performance of construction facilities. Moisture, precipitation, wind loads, ultraviolet radiation, and cyclic temperature fluctuations directly affect the physical and mechanical properties of facade materials in outdoor environments [7; 19; 20]. As a result, material deterioration accelerates, protective properties decline, and additional maintenance and repair costs arise [9]. Therefore, a comprehensive assessment of atmospheric impacts on facade systems and the development of technological solutions aimed at mitigating their effects are of significant scientific and practical importance.

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The analysis indicates that moisture and repeated temperature fluctuations are among the most critical factors affecting facade materials [7; 20]. Moisture penetration into material structures intensifies corrosion processes, causes the formation of microcracks in concrete and composite materials, and reduces the overall strength of structural components [17]. Sharp temperature variations lead to thermal expansion and contraction of materials, which negatively affects their operational performance over time [19].

Table 1. Impact of Atmospheric Factors on Facade Materials.[1]

Atmospheric Factor	**Impact Level**	**Primary Consequence**
Moisture and Precipitation	High	Corrosion and material deterioration
UV Radiation	High	Color fading and material aging
Wind Loads	Medium–High	Mechanical damage
Freeze–Thaw Cycles	High	Formation of microcracks
Air Pollution	Medium	Surface degradation of materials

The data presented in Table 1 indicate that atmospheric influences are among the primary factors reducing the service life of facade systems. Therefore, the use of protective coatings and weather-resistant materials has become increasingly important in modern construction practice [1; 17].

Nanocoatings and hydrophobic protective treatments are recognized as effective technological solutions for mitigating the adverse effects of atmospheric factors [1; 18]. Research findings show that nanocoatings create an additional protective layer on material surfaces, significantly reducing water penetration into internal structural layers [1]. Moreover, they enhance resistance to ultraviolet radiation and help preserve the color stability and physical properties of facade materials over extended periods [9]. Hydrophobic coatings, on the other hand, prevent water droplets from remaining on material surfaces, thereby slowing down moisture-related deterioration processes [18].

Structural solutions also play a crucial role in improving the resistance of facades to atmospheric impacts. In particular, ventilated facade systems create conditions for natural air circulation between the facade cladding and the main wall structure [5]. As a result, moisture accumulation is reduced and materials remain in a dry condition for longer periods [13]. Studies indicate that buildings equipped with

[1] Manba: xalqaro tadqiqotlar asosida muallif tomonidan tuzildi.

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ventilated facade systems demonstrate greater service life and higher operational efficiency compared to conventional facade solutions [5].

Table 2. Technologies for Improving the Resistance of Facades to Atmospheric Impacts.[2]

Technology Type	Primary Function	Expected Outcome
Nanocoatings	Protection against moisture and UV radiation	Extended service life
Hydrophobic Coatings	Reduction of water absorption	Reduced material deterioration
Ventilated Facade Systems	Moisture removal and ventilation	Improved operational stability
Composite Materials	Mechanical and chemical resistance	Enhanced structural strength
Adaptive Facade Systems	Adaptation to environmental conditions	Reduced impact of atmospheric loads

Another important factor affecting the service life of facades is related to the structural properties of materials. The reviewed studies indicate that composite materials exhibit a high level of resistance to atmospheric influences [12; 19]. Compared with conventional materials, these materials demonstrate superior performance in terms of moisture resistance, corrosion resistance, and mechanical strength [12]. Consequently, the use of composite panels and multilayer protective systems in the construction of high-rise building facades has become increasingly widespread in many developed countries [10].

The development of facade technologies has also been driven by the emergence of adaptive and intelligent systems, which provide new opportunities for improving facade performance [4; 6]. These technologies are capable of adapting to changing environmental conditions and help reduce the atmospheric loads acting on facade materials [6]. By responding to variations in solar radiation, humidity, and temperature, adaptive facades contribute to maintaining the long-term stability and durability of building structures [4].

[2] Manba: xalqaro manbalar asosida tuzildi.

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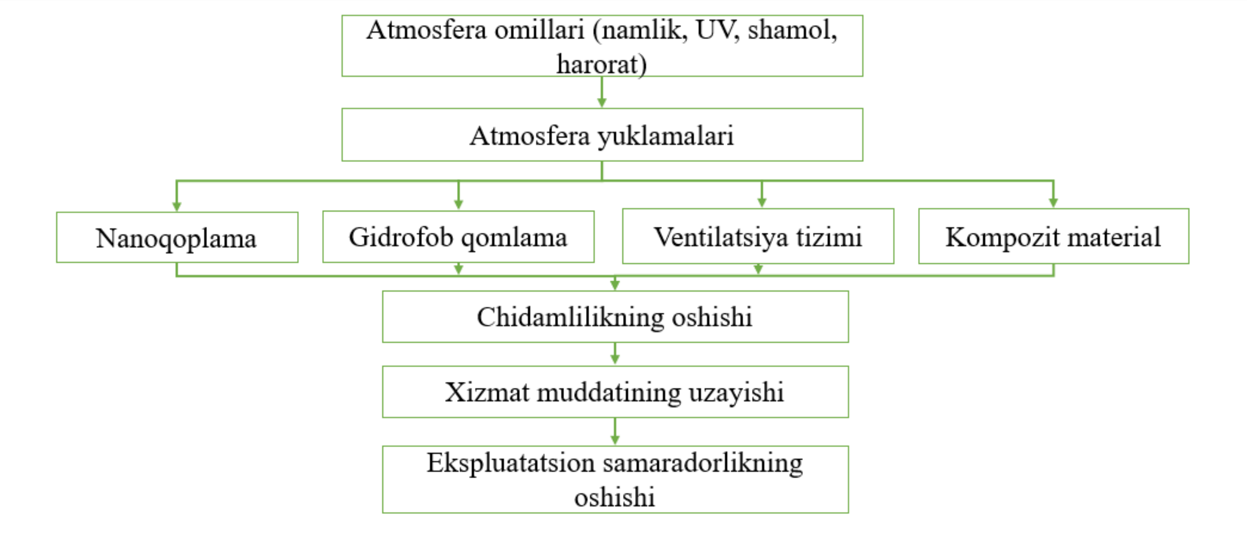

Figure 1.

Mechanism for Enhancing the Resistance of High-Rise Building Facades to Atmospheric Impacts.[3]

The figure illustrates a step-by-step mechanism for improving the resistance of high-rise building facades to atmospheric impacts.

At the top of the figure, the main atmospheric factors affecting facade systems are presented, including moisture, ultraviolet (UV) radiation, wind loads, and temperature fluctuations. These factors negatively influence the physical and mechanical properties of facade materials, accelerate deterioration processes, and reduce their service life [7; 19; 20].

To mitigate the effects of these environmental loads, the application of modern protective technologies is required. As shown in the figure, these technologies include nanocoatings, hydrophobic coatings, ventilated facade systems, and composite materials.

Nanocoatings create a protective layer on facade surfaces, reducing the harmful effects of moisture and ultraviolet radiation [1]. Hydrophobic coatings limit water penetration into materials, thereby slowing corrosion and deterioration processes [18]. Ventilated facade systems prevent moisture accumulation within the structure, improve air circulation, and help maintain materials in a dry condition [5]. Composite materials are distinguished by their high mechanical strength and superior resistance to atmospheric influences [12; 19].

[3] Manba: muallif ishlanmasi

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The combined application of these technologies significantly enhances the resistance of facades to atmospheric impacts. Improved durability helps maintain the technical condition of facade systems over extended periods. Consequently, the service life of facades is prolonged, the intervals between maintenance and rehabilitation activities become longer, and operational costs are reduced [8; 14].
The final outcome presented in the figure is an increase in operational efficiency. This contributes to more rational use of resources, lower maintenance expenditures, and improved long-term economic performance of high-rise buildings [10; 14].

CONCLUSIONS AND RECOMMENDATIONS

The conducted research demonstrated that the resistance of high-rise building facades to atmospheric impacts is one of the key factors determining their operational efficiency and service life. The literature review and analysis of international experience confirmed that moisture, ultraviolet radiation, wind loads, and cyclic temperature variations accelerate the deterioration of facade materials, resulting in increased maintenance and repair costs [7; 19; 20].
The findings indicate that nanocoatings, hydrophobic protective treatments, ventilated facade systems, and modern composite materials represent highly effective technological solutions for mitigating the adverse effects of atmospheric factors [1; 5; 12]. These technologies help limit moisture penetration into structural components, slow down corrosion and deterioration processes, and preserve the physical and mechanical properties of facade materials over extended periods [8; 17].
The study further revealed that improving facade durability cannot be achieved through the application of individual technologies alone. Greater effectiveness is attained through the integrated use of protective coatings, structural solutions, and weather-resistant materials [5; 14]. In particular, the combined application of ventilated facade systems and nanocoatings proved to be an efficient approach for reducing moisture-related damage and extending the service life of facade structures [1; 5].
Based on the obtained results, it is recommended to increase the use of weather-resistant composite materials in the design and construction of high-rise building facades. Furthermore, wider implementation of nanocoatings and hydrophobic protective treatments, greater adoption of ventilated facade systems, and the

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evaluation of atmospheric resistance indicators during the design stage are strongly recommended [12; 18; 19].

Overall, the extensive application of weather-resistant facade technologies contributes to extending the service life of high-rise buildings, reducing operational costs, and ensuring the long-term structural stability of construction facilities. Consequently, these technologies represent an important factor in enhancing quality, reliability, and economic efficiency within the construction industry [10; 14].

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