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REVIEW ARTICLE

THERMAL AND ACOUSTIC INSULATION METHODS FOR WOODEN WINDOW UNITS IN KAZAKHSTAN: A REVIEW

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Abstract. *Improving the thermal and acoustic insulation of wooden window units is increasingly important for building energy efficiency and indoor comfort, especially in continental climates. In south-eastern Kazakhstan, including Almaty, strong seasonal temperature contrasts, dry cold winters, and hot summers accelerate material ageing and can reduce the long-term performance of facade elements, making window-system optimization a priority. This review is based on a systematic analysis of peer-reviewed studies and current regulatory and technical documents on wooden window design and performance. The solutions considered include wood-based frame systems, multi-pane insulating glass units, low-emissivity (Low-E) coatings, inert gas filling, vacuum glazing, acoustic laminated glass, and improved sealing and insulation of installation joints. Attention is given to EPDM gaskets as durable sealing materials resistant to temperature-induced deformation and ageing. The analysed evidence shows a consistent improvement trend in thermal performance: the overall thermal transmittance (U-value) decreases from about 1.1 W/(m2·K) for conventional insulating glass units to around 0.4 W/(m2·K) when vacuum glazing is applied. Acoustic laminated glass and multi-contour sealing systems also improve sound insulation performance, while frame geometry, profile design, and material selection determine the integrated thermal-acoustic effect. The review concludes that the most effective strategy for Kazakhstan is an integrated approach combining advanced glazing, optimized wooden frames, and reliable sealing systems to reduce heat losses, improve acoustic comfort, and meet modern energy-efficiency and safety requirements.*

Keywords *wooden window units, multi-pane glazing, vacuum glazing, low-emissivity coatings, sound insulation, continental climate.*

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ШОЛУ МАҚАЛАСЫ

ҚАЗАҚСТАНДАҒЫ АҒАШ ТЕРЕЗЕ БЛОКТАРЫНЫҢ ЖЫЛУ ЖӘНЕ ДЫБЫС ОҚШАУЛАУ ӘДІСТЕРІНЕ ШОЛУ

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Аңдатпа. *Ағаш терезе блоктарының жылу және дыбыс оқшаулау қасиеттерін жақсарту ғимараттардың энергия тиімділігін арттыру және ішкі ортада қолайлы жағдай қалыптастыру үшін, әсіресе континенттік климат жағдайында, маңызды болып табылады. Қазақстанның оңтүстік-шығыс өңірінде, оның ішінде Алматы қаласында, маусымдық температура айырмашылықтарының айқын болуы, қыстың суық әрі құрғақ, ал жаздың ыстық болуы материалдардың қартаю үдерістерін жеделдетіп, қоршаушы конструкция элементтерінің ұзақ мерзімді пайдалану сипаттамаларын төмендетуі мүмкін. Осыған байланысты терезе жүйелерін оңтайландыру басым міндеттердің бірі болып табылады.Бұл шолу ағаш терезе блоктарын жобалау мен олардың пайдалану сипаттамаларына арналған рецензияланатын ғылыми еңбектерді және қолданыстағы нормативтік-техникалық құжаттарды жүйелі талдау негізінде дайындалған. Зерттеу барысында ағаш негізіндегі рамалық жүйелер, көпқабатты әйнек пакеттері, төмен эмиссиялы (Low-E) жабындар, әйнек аралық кеңістікті инертті газбен толтыру, вакуумдық әйнектеу және акустикалық ламинатталған әйнек сияқты шешімдер қарастырылған. Сонымен қатар, монтаждық жіктерді герметизациялау және жылу оқшаулау тәсілдеріне, сондай-ақ этилен-пропилен-диен каучугі (EPDM) негізіндегі тығыздағыштарды қолданудың маңыздылығына ерекше назар аударылған. Талдау нәтижелері жылу өткізгіштік коэффициентінің (U-value) дәстүрлі әйнек пакеттері үшін шамамен 1,1 Вт/(м²·К) мәнінен вакуумдық әйнектеу қолданылған жағдайда шамамен 0,4 Вт/(м²·К) деңгейіне дейін төмендейтінін көрсетеді. Акустикалық ламинатталған әйнек пен көпконтурлы тығыздау жүйелері дыбыс оқшаулау тиімділігін арттырады. Қорытындысында Қазақстан жағдайында ең тиімді шешім ретінде кешенді тәсіл ұсынылады, ол энергия үнемдеуге, ұзақ мерзімді сенімділікке және тұрғындардың акустикалық жайлылығына ықпал етеді.*

Түйін сөздер: *ағаш терезе блоктары, көпқабатты әйнектеу, вакуумдық әйнектеу, төмен эмиссиялы жабындар, дыбыс оқшаулау, континенттік климат.*

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ОБЗОРНАЯ СТАТЬЯ

ОБЗОР МЕТОДОВ ТЕПЛО- И ЗВУКОИЗОЛЯЦИИ ДЕРЕВЯННЫХ ОКОННЫХ БЛОКОВ В КАЗАХСТАНЕ

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Аннотация. *Повышение тепло- и звукоизоляционных характеристик деревянных оконных блоков является важной задачей в условиях повышения требований к энергоэффективности зданий и обеспечению комфортной внутренней среды, особенно в регионах с континентальным климатом. В юго-восточном Казахстане, включая город Алматы, выраженные сезонные температурные контрасты, холодные зимы и жаркое лето ускоряют процессы старения материалов и снижают долговечность элементов ограждающих конструкций, что делает оптимизацию оконных систем актуальной. Настоящий обзор основан на систематическом анализе рецензируемых научных публикаций и действующих нормативно-технических документов, посвящённых проектированию и эксплуатационным характеристикам деревянных оконных блоков. Рассмотрены современные материалы и инженерные решения, включая деревянные рамные системы, многокамерные стеклопакеты, низкоэмиссионные покрытия (Low-E), заполнение межстекольного пространства инертным газом, вакуумное остекление и акустическое ламинированное стекло. Отдельное внимание уделено системам герметизации монтажных швов и применению уплотнителей на основе этилен-пропилен-диенового каучука (EPDM). Результаты анализа показывают снижение коэффициента теплопередачи (U-value) с ~1,1 до ~0,4 Вт/(м²·К) при использовании вакуумного остекления. Сделан вывод о целесообразности комплексного подхода для повышения энергоэффективности и акустического комфорта зданий в условиях Казахстана.*

Ключевые слова: *деревянные оконные блоки, многокамерное остекление, вакуумное остекление, низкоэмиссионные покрытия, звукоизоляция, континентальный климат.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

The authors declare that no generative artificial intelligence technologies or AI-based tools were used in the preparation of this article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Авторлар мақаланы дайындау барысында генеративті жасанды интеллект технологиялары мен жасанды интеллектке негізделген технологияларды пайдаланбағанын мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

Авторы заявляют о том, что при подготовке статьи не использовались технологии генеративного искусственного интеллекта и технологии, основанные на искусственном интеллекте.

1 INTRODUCTION

With the increasing density of urban development and the growth of transport flows, the problem of protecting buildings from heat loss and external noise has become increasingly relevant. Window openings are widely recognised as the least thermally resistant elements of the building envelope and often act as primary paths for heat losses and noise penetration. Therefore, ensuring high thermal and acoustic performance of window systems is a key factor in improving the overall energy efficiency of buildings and maintaining comfortable indoor environmental conditions, particularly in urban areas (**Cuce, 2018; Kaliev & Amanzholov, 2022**).

At the international level, window technologies have become an active field of research, as windows may account for up to 25% of a building envelope while contributing up to 50-60% of total heat losses (**Moghaddam et al., 2023**). Numerous studies indicate that traditional wooden window units with single or conventional double glazing and basic sealing systems often fail to comply with modern regulatory requirements for thermal transmittance and sound insulation. In particular, such systems frequently do not meet the criteria specified in standards such as **EN ISO 10077-1:2021**, **GOST 23166-99**, and **SP 50.13330.2024**.

In recent years, significant attention has been given to the development of advanced wooden window systems incorporating double or triple insulating glass units with inert gas fillings, vacuum glazing, acoustic laminated glass, and glued laminated timber frames with improved thermal performance. These solutions allow a substantial reduction in the heat transfer coefficient, typically to values of 0.5-0.8 W/(m²·K), while achieving sound insulation levels of approximately 35-40 dB, thereby considerably outperforming conventional window designs (**Ahn & Park, 2020; Miskinis et al., 2016; Peng et al., 2025**).

Despite these advances, a number of unresolved issues remain. High cost, increased structural weight, and limited durability of individual components continue to restrict the widespread application of high-performance window systems. In particular, some sealing materials, such as unprotected polyurethane gaskets, exhibit accelerated degradation under conditions of high humidity and pronounced temperature fluctuations characteristic of continental climates, where seasonal temperatures may range from -30 °C to +35 °C (**Flimel, 2016**). These factors highlight the need for more durable and climate-adapted solutions.

In this context, the present article aims to review engineering and design approaches for improving the thermal and acoustic insulation performance of wooden window units. The analysis focuses on structural solutions based on wood-derived materials combined with multilayer glazing, sealing, and insulating components, with particular emphasis on their applicability under the climatic conditions of southeastern Kazakhstan.

Research on the thermal and acoustic insulation performance of window systems has been actively conducted since the late twentieth century. However, between 2010 and 2025, interest in this field has increased significantly due to the tightening of building energy-efficiency regulations and the growing demand for sustainable construction solutions. Previous studies indicate that window openings represent one of the weakest components of the building envelope in terms of thermal resistance, accounting for up to 50-60% of total heat losses even in buildings with well-insulated walls and roofs (**Cuce, 2018**). In parallel, the issue of protecting indoor environments from external noise has become increasingly important, particularly in densely built urban areas and near major transport corridors (**Dulak & Nowoswiat, 2025**).

A substantial body of international research demonstrates that the thermal and acoustic performance of window systems can be significantly improved through the use of multi-layer glazing configurations, low-emissivity (Low-E) coatings, and inert gas fillings such as argon, krypton, or xenon (**Moghaddam et al., 2023; van Nieuwenhuijzen et al., 2023; Duan et al., 2020**). Among advanced technologies, vacuum-insulated glazing (VIG) is considered one of the most efficient solutions, offering heat transfer coefficients (U-values) as low as 0.4–0.5 W/(m²·K) at relatively small overall thickness (**Jung et al., 2024; Peng et al., 2025; Pont et al., 2019**). Nevertheless, the high production cost and technological complexity of vacuum glazing currently limit its widespread application in standard residential construction.

In addition to glazing systems, several studies emphasize the importance of frame design in achieving high insulation performance. According to **Ahn and Park (2020)** and **Ostapska et al. (2023),** the thermal behavior of wooden window frames is strongly influenced by wood species, fiber orientation, and structural configuration. Compared to aluminum profiles, wooden frames-especially those made from softwood lamellae-exhibit substantially lower thermal conductivity. The use of glued laminated timber further improves dimensional stability and resistance to deformation, while the integration of thermal breaks within frame profiles contributes to additional reductions in heat losses. At the same time, the long-term durability of wood under cyclic humidity and temperature variations remains a key research concern.

Acoustic insulation of wooden window units has also been extensively studied. One of the most effective approaches involves the use of laminated glass with acoustic polymer interlayers, which can increase the weighted sound reduction index (R_w) to 36-40 dB (**Miskinis et al., 2016; Granzotto et al., 2017; Bartnik et al., 2022; Berardi et al., 2025**). Research shows that sound insulation performance depends not only on glazing thickness and composition, but also on frame stiffness, joint tightness, and overall installation quality (**Buratti et al., 2013**).

The role of sealing systems is highlighted in multiple studies as a critical factor influencing both thermal and acoustic performance. According to **Flimel (2016),** sealing materials must maintain elasticity and airtightness across a wide temperature range, typically from -30 °C to +35 °C, to accommodate wood deformation and prevent air leakage. Failure of sealing components can significantly reduce the effectiveness of even highly efficient glazing systems.

Despite considerable progress in window technologies, the reviewed literature identifies several persistent challenges. These include the high cost of advanced glazing solutions, increased structural weight, and the need for adaptation to specific climatic conditions. In regions characterized by continental climates with sharp seasonal temperature variations, careful selection of wood species, adhesives, coatings, and sealing materials is essential (**Mehdizadeh-Rad et al., 2022**). Overall, the literature indicates that further optimization of wooden window systems is required to balance thermal and acoustic performance, durability, and economic feasibility under regional climatic conditions.

Wood has long been used as a structural material for window frames due to its favorable thermal, mechanical, and environmental properties. According to published data, at an average moisture content of approximately 12%, the thermal conductivity coefficient (λ) of wood ranges from 0.10-0.17 $W \cdot m^{-1} \cdot K^{-1}$ for softwood species and from 0.15-0.21 $W \cdot m^{-1} \cdot K^{-1}$ for certain hardwood species, which is significantly lower than that of metallic materials commonly used in window systems (**Ahn & Park, 2020; Flimel, 2016**).

Wood exhibits pronounced anisotropy in thermal behavior. Thermal conductivity along the fiber direction is approximately two to two and a half times higher than in radial or tangential directions. As a result, the orientation of annual rings and fibers plays a crucial role in the thermal performance of wooden window frames. In addition, thermal conductivity is closely related to density: under similar conditions, less dense softwoods generally demonstrate lower λ-values than denser hardwoods.

Due to its hygroscopic nature, wood undergoes shrinkage and swelling in response to changes in ambient humidity, leading to anisotropic deformation. To mitigate these effects, modern window frames are commonly manufactured from glued laminated timber (glulam), composed of multiple lamellas with alternating fiber orientations. This structural configuration improves dimensional stability, reduces internal stresses, and minimizes the influence of natural defects present in solid wood (**Ostapska et al., 2023; Sambetbayeva & Kurmanbekova, 2022**). The linear coefficient of thermal expansion of wood is relatively low, approximately $\alpha \approx (5\text{-}6) \times 10^{-6}\ K^{-1}$, which is substantially lower than that of polymer-based profiles such as PVC, where $\alpha \approx 70 \times 10^{-6}\ K^{-1}$ (**Paulos & Berardi, 2020; Knight et al., 2024**).

From a structural perspective, wooden frames provide sufficient load-bearing capacity for small- and medium-sized glazing units without the need for additional metal reinforcement. In contrast, plastic window systems typically require steel inserts, which can create thermal bridges and negatively affect overall thermal performance (**Ahn & Park, 2020**). Furthermore, wood possesses inherent internal damping properties, which contribute to vibration reduction. Nevertheless, the sound insulation performance of a complete window unit remains largely dependent on glazing composition and sealing effectiveness rather than frame material alone.

In terms of sustainability, wood is a renewable resource and is associated with relatively low carbon emissions during production compared to aluminum or synthetic materials. Life-cycle assessment studies indicate that wooden window frames exhibit favorable environmental performance when appropriate protective coatings and maintenance practices are applied (**Moghaddam et al., 2023**). Proper surface treatment with paints or varnishes is essential to prevent moisture ingress, biological degradation, and weathering. At the end of their service life, wooden components can be recycled or disposed of in an environmentally safe manner.

Based on the reviewed literature, three key factors determine the suitability of wood for window frame applications:

- low thermal conductivity combined with anisotropic heat transfer behavior;
- sensitivity to moisture, requiring constructive solutions that enhance dimensional stability, such as laminated profiles and controlled grain orientation;
- the necessity of protective finishing systems and regular maintenance to ensure long-term durability.

These material characteristics are considered in conjunction with glazing systems and sealing technologies in subsequent sections of the review.

2 MATERIALS AND METHODS

Most of the reviewed publications fall within the 2010-2025 period, which covers both well-established engineering approaches and the recent progress in high-performance glazing and sealing technologies.

Search queries combined keywords such as wooden window units, thermal insulation, acoustic performance, vacuum glazing, laminated glass, Low-E coatings, thermally broken frames, gasket durability, continental climate, and building energy efficiency. Boolean operators (AND, OR) were used, and results were filtered by publication year, document type, and peer-review status.

The selection procedure followed two steps. First, titles and abstracts were screened to identify studies directly relevant to thermal and acoustic performance of wooden window assemblies. Second, full texts were examined to extract reported performance indicators and implementation details. Preference was given to studies presenting quantitative thermal metrics (including U-values) and acoustic indices (including R_w), as well as durability observations under variable temperature and humidity. Papers without sufficient technical detail or without performance data were not included. Duplicate records retrieved from different databases were removed.

To organize the evidence, the selected materials were grouped into three categories: glazing solutions, frame design, and sealing and installation practices. Performance results were compared within comparable boundary conditions where possible and interpreted with reference to standardized approaches described in **EN ISO 10077-1:2021**. In parallel, regulatory documents relevant to window design and installation, including **GOST 23166-99** and **SP 50.13330.2024**, were reviewed to align the synthesis with current requirements. The final synthesis highlights performance ranges, dominant development trends, and practical solutions applicable to the climatic conditions of south-eastern Kazakhstan.

3 RESULTS AND DISCUSSION

A comparative analysis of published studies shows that the use of double-glazed insulating glass units (IGUs) with low-emissivity (Low-E) coatings and inert gas fillings (argon, krypton) can reduce the overall heat transfer coefficient (U-value) to 0.9-1.1 $W/(m^2 \cdot K)$, which is approximately 35-40 % more efficient compared to conventional single-glazed systems (U ≈ 2.2-2.6 $W/(m^2 \cdot K)$) (**Cuce, 2018; Ahn & Park, 2020; Onatayo et al., 2024**). A comparison of U-values for different glazing configurations is presented in **Figure 2**. The structural configuration of a modern energy-efficient wooden window is presented in **Figure 1**, which shows a glued laminated timber frame combined with a triple-glazed unit, Low-E coating, and a multi-contour sealing system.

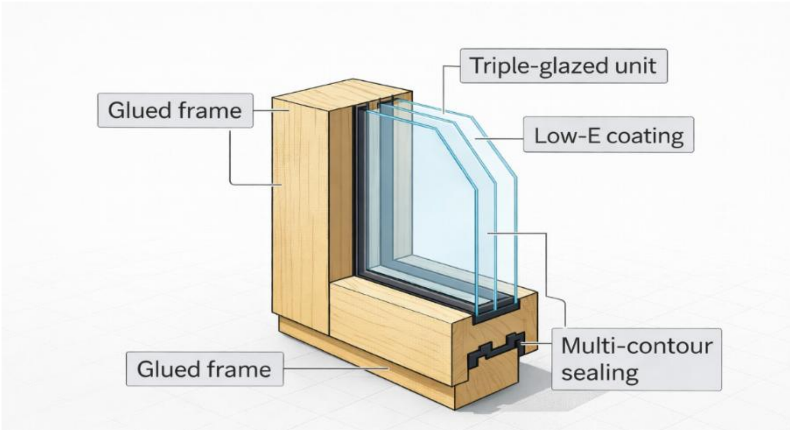


Figure 1 – Structural scheme of a modern wooden window unit with triple glazing, low-emissivity coating, and multi-contour sealing (author's material)

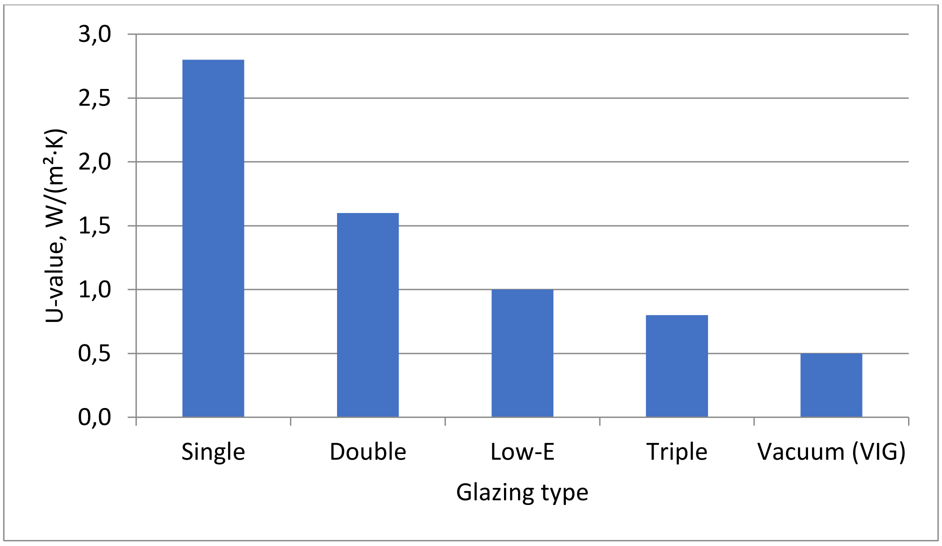


Figure 2 – Comparison of heat transfer coefficients (U-values) of different glazing types (author's material)

According to the literature, such glazing configurations significantly reduce heat losses during winter and the risk of overheating in summer under the climatic conditions of southeastern Kazakhstan. The use of laminated glass with acoustic interlayers increases the sound insulation index (R_w) up to 38–42 dB (**Miskinis et al., 2016; Granzotto et al., 2017; Bliūdžius et al., 2022; Schuster et al., 2023**), which is particularly important for buildings located near major transportation routes.

Studies show that solid wooden frames exhibit significantly lower thermal conductivity compared to aluminum ones, although they remain sensitive to fluctuations in humidity and temperature. Publications describe the implementation of glued laminated timber (glulam) lamellas with integrated thermal breaks, which enhance dimensional stability and reduce the U-value of frames by

15–20% compared to conventional solid wood profiles (**Ahn & Park, 2020; Ostapska et al., 2023**). The introduction of an additional sealing contour along the frame perimeter further decreases air infiltration by approximately 25% on average.

Separate studies also discuss the combination of materials and the filling of internal cavities with insulating inserts (e.g., basalt wool) to improve thermal and acoustic insulation (**Sambetbayeva & Bolatova, 2025**). Wood–aluminum hybrid systems with external aluminum cladding combine the durability of aluminum with the thermal efficiency of wood, although the overall thermal resistance of such composite frames is slightly lower than that of fully wooden ones due to the presence of metal elements. As shown in **Figure 3**, an increase in the number of glass layers leads to higher sound insulation performance.

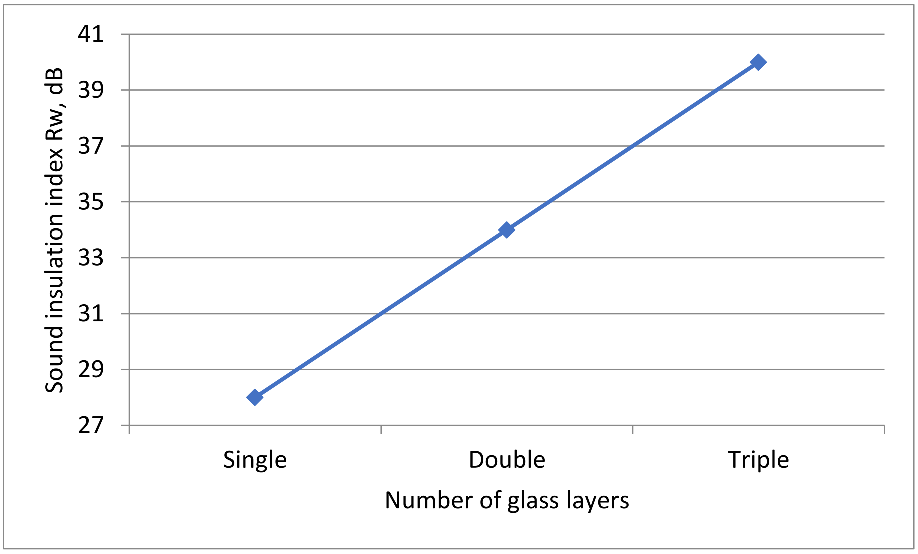


Figure 3 - Dependence of the sound insulation index (Rw) on the number of glass layers (author's material)

An increase in the number of glass panes and the use of laminated glazing enhance the sound insulation index (R_w); however, the improvement becomes less significant beyond three layers. The structure of a three-chamber insulating glazing unit is shown in **Figure 4**. At the same time, research focuses on lightweight frame design without compromising structural strength: the use of high-strength adhesive compositions and optimized frame geometry allows for a reduction in the visible frame width while maintaining the required thermal and acoustic insulation performance (**Ostapska et al., 2023; Verichev et al., 2025**).

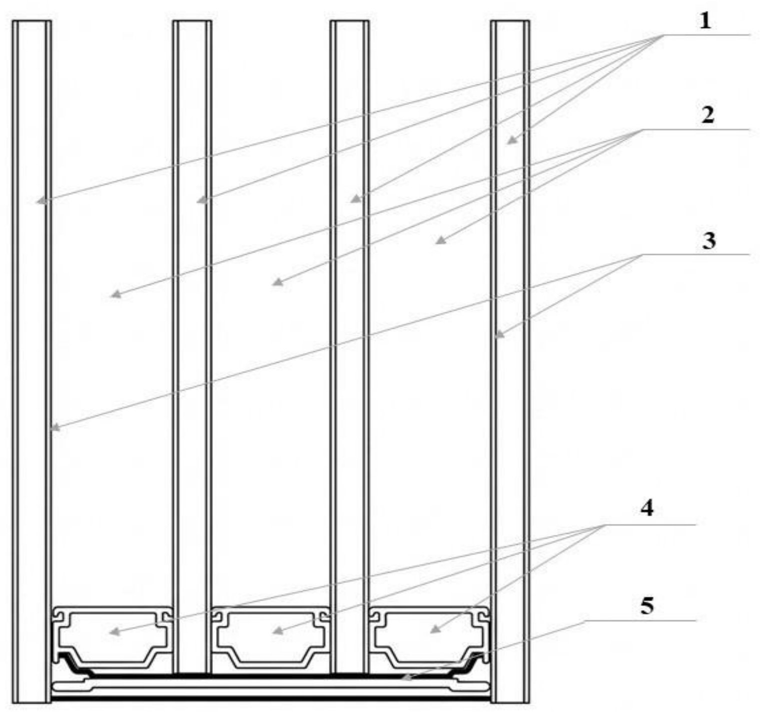
Reviews emphasize the critical role of sealing materials and adhesives in ensuring the durability and energy efficiency of window assemblies. Seals based on synthetic rubbers, such as EPDM (Ethylene Propylene Diene Monomer), and thermoplastic elastomers maintain elasticity and airtightness within a temperature range from -30 to +40 °C. The triple-contour EPDM sealing system significantly reduces uncontrolled air infiltration (**Figure 6**). In contrast, earlier PVC-based seals lost flexibility at approximately -15 °C, leading to increased air leakage (**Buratti et al., 2013; Flimel, 2017**). The use of polyurethane adhesives in the assembly of wooden frames enhances the strength of corner joints by 20-25 % and improves the moisture resistance of bonded connections (**Kurmanbekova & Sambetbayeva, 2022**). The structural classification of technologies used for thermal and acoustic improvement is presented in **Figure 7**.

The key performance criteria used in the literature to evaluate the effectiveness of sealing and bonding solutions include:

- Airtightness (air permeability or infiltration rate along the perimeter, $m^3/(m \cdot h)$ under a given pressure difference ΔP);

- Elasticity retention of sealing materials after climatic cycling (-30…+40 °C);
- Adhesive joint strength (shear or peel resistance after conditioning);
- Moisture resistance (mass exchange or swelling behavior under humid exposure);
- Contribution to overall window performance, including reduced U-value and increased sound insulation index (R_w) relative to baseline configurations.

A comparative overview of U-values and R_w indices for different glazing systems is presented in **Figure 5**.



1 – Glass sheet; 2 – Gap filled with argon gas; 3 – Low emissivity coating; 4 – Spacer; 5 – Sealing.

Figure 4 – Cross-section of a four-pane three-chamber insulating glazing unit with Low-E coating and argon filling (author's material)

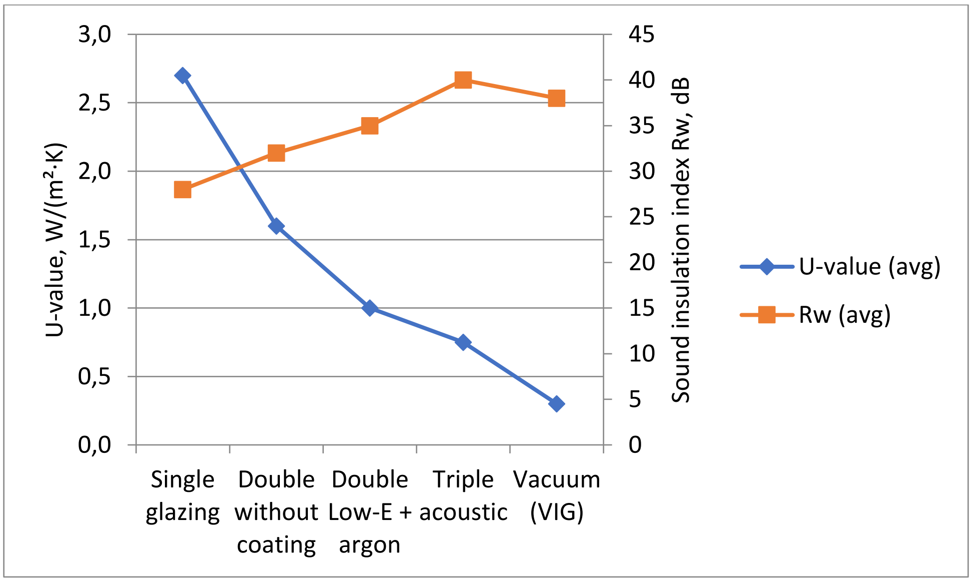


Figure 5 - Comparison of thermal (U-value) and acoustic (Rw) performance of window units with different glazing configurations (author's material)

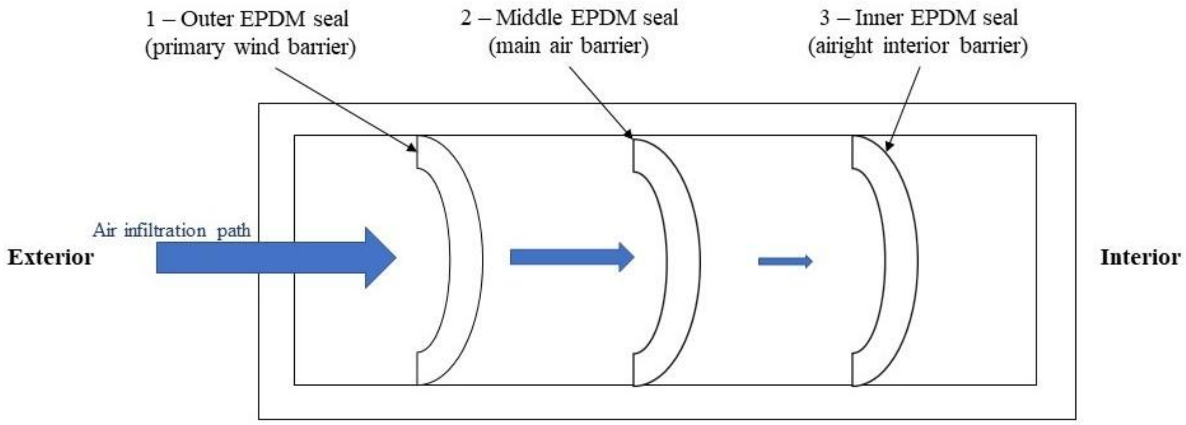


Figure 6 – Principle of triple-contour EPDM sealing system and reduction of air infiltration (author's material)

As the glazing configuration becomes more complex, the U-value decreases while the Rw index increases (**Aubakirova & Aidarbayeva, 2022**). The overall insulating effect is reinforced by high-quality installation practices, including the use of low-expansion mounting foams and vapor- and moisture-proof sealing tapes, which help minimize uncontrolled air infiltration through installation joints.

Based on literature sources and manufacturers' data sheets, the ranges of U-values and R_w indices for common glazing configurations were synthesized (**Table 1**).

Table 1.
Comparison of Thermal and Acoustic Insulation Characteristics of Glazing (author's material)

Glazing type	$U, W/(m^2 \cdot K)$	R_w, dB	Application notes
Single glazing	2.5-2.8	26-28	Very high heat losses, low sound insulation
Double glazing (no special coatings)	1.6-1.8	30-32	Moderate energy efficiency, limited noise protection
Double glazing with Low-E and argon	0.9-1.1	34-36	Balanced option for the climatic conditions of southeastern Kazakhstan
Triple glazing with acoustic interlayer	0.7-0.8	38-42	High sound insulation, increased cost
Vacuum insulating glazing (VIG)	0.4-0.5	36-38	Maximum thermal insulation at minimal thickness (high cost)

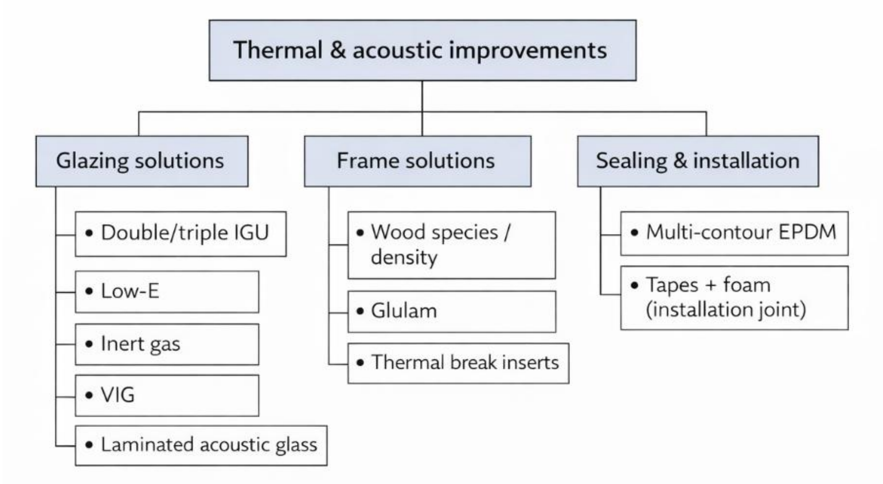


Figure 7 – Structural classification of thermal and acoustic improvement technologies in modern window systems (author's material)

The frame material has a significant impact on the resulting U-value. A comparison of the key thermophysical properties of commonly used frame materials is presented below (Table 2).

Table 2.
Comparison of Thermophysical Properties of Window Frame Materials (author's material)

Material	Thermal conductivity λ, $W/(m^2 \cdot K)$	Density, kg/m^3
Wood (pine)	~0.12–0.15	~500
PVC	~0.17	~1400
Aluminum (alloy)	~160	~2700

According to the data in Table 2, wood exhibits the lowest thermal conductivity among the listed materials. Aluminum without a thermal break conduct heat approximately one thousand times more intensively than a wooden element of the same thickness. PVC is close to wood in terms of λ but requires steel reinforcement (which forms a thermal bridge) and has a high coefficient of linear thermal expansion ($\approx 7 \times 10^{-5}$ 1/K), leading to noticeable thermal deformation of long profiles. With sufficient thickness, wooden and PVC frames provide a comparable level of sound insulation (Rw), whereas lightweight aluminum profiles perform slightly worse due to lower internal damping properties. The influence of frame material on heat transfer intensity is illustrated in Figure 8.

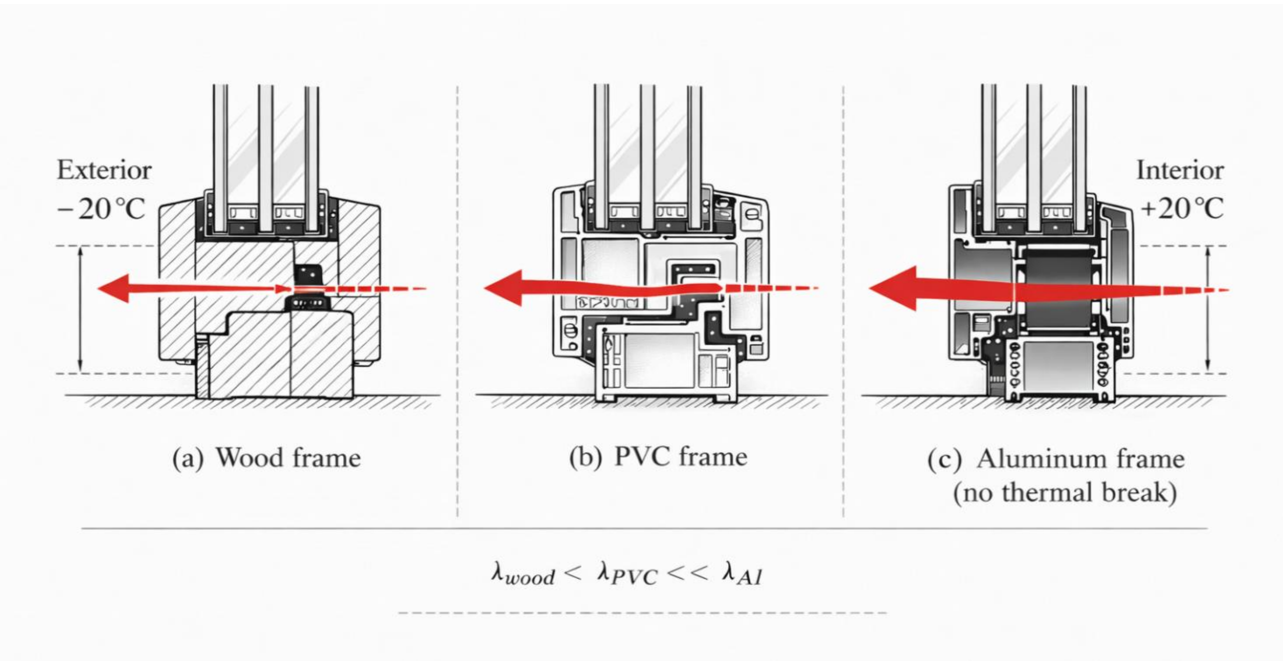


Figure 8 – Comparative heat flow through wooden, PVC and aluminum window frames under identical temperature difference conditions (author's material)

An illustrative heat loss calculation demonstrates the influence of glazing type and frame material under a temperature difference of $\Delta T = 40°C$ and the window area of $A = 1m^2$. The heat flux through the window can be determined using the expression shown in Equation (1):

$$Q = U \cdot A \cdot \Delta T, \quad (1)$$

where:
Q- heat loss, W;
U - heat transfer coefficient of the window unit,$W/(m^2 \cdot K)$;
A - window area, m^2;
ΔT - temperature difference between indoor and outdoor environments, °C.

For single glazing with a simple wooden frame ($U \approx 2.6W/(m^2 \cdot K)$), the heat loss is approximately Q ≈ 104 W. In contrast, for triple glazing with Low-E coating and argon filling ($U \approx$

$0.8W/(m^2 \cdot K)$), the value decreases to $Q \approx 32\ W$, corresponding to about a 70% reduction in heat loss under otherwise identical conditions. According to (**Moghaddam et al., 2023**), even the replacement of glazing alone in existing window units can lead to 15-30% savings in heating costs.

Overall, the comparison shows that the lowest heat transfer coefficients (U) are achieved in Vacuum Insulated Glazing (VIG) systems; however, their wide adoption remains limited due to high cost and technological complexity (**Qiu et al., 2025; Uddin et al., 2023**). The most balanced solution for the climatic conditions of southeastern Kazakhstan remains double glazing with Low-E coating and argon filling ($U \approx 1.0W/(m^2 \cdot K)$ $R_w \approx 34 - 36dB$), providing an optimal balance between thermal performance and affordability.

4 CONCLUSIONS

1. The review confirms that window openings remain one of the main pathways for heat loss and external noise penetration. Under the continental climatic conditions of Kazakhstan, improving the thermal and acoustic performance of wooden window units is essential for reducing energy consumption and ensuring indoor comfort.
2. Modern glazing technologies significantly enhance insulation performance. Double and triple insulating glass units with Low-E coatings and inert gas fillings reduce U-values to approximately 0.9-1.1 $W/(m^2 \cdot K)$, while vacuum glazing can achieve values of about 0.4-0.5 $W/(m^2 \cdot K)$. Acoustic laminated glass increases sound insulation up to 38-42 dB, although widespread implementation is constrained by cost and technological complexity.
3. Wooden window frames demonstrate favorable thermal, structural, and environmental properties compared to aluminum and PVC systems. The use of glued laminated timber improves dimensional stability under variable temperature and humidity conditions; however, durability strongly depends on protective coatings and maintenance strategies.
4. Sealing systems and installation quality play a decisive role in maintaining window performance throughout service life. EPDM-based gaskets and properly insulated installation joints effectively reduce air infiltration and help preserve both thermal and acoustic efficiency.
5. The analysis shows that the most practical solution for southeastern Kazakhstan is an integrated approach combining double glazing with Low-E coatings and argon filling, optimized wooden frames, and reliable multi-contour sealing systems.

Future research should focus on reducing the cost of high-performance glazing, conducting long-term experimental durability assessments of sealing materials under continental climate conditions, and developing region-specific design recommendations aligned with current national and international standards.

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