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Systematic Review

A Conceptual Framework for Biophilic Architectural Design in Cold Climates: A Meta-Synthesis Analysis

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Abstract

Biophilic design has traditionally evolved from temperate-zone contexts, where access to nature is more readily available, and has rarely addressed the challenges of extreme climatic conditions. The potential of biophilic design to enhance health and well-being in cold environments, where exposure to nature must adapt to low temperatures, limited solar radiation, and pronounced photoperiod variation, remains underexplored. This study conducts a systematic meta-synthesis of biophilic architectural design strategies in Arctic and Sub-Arctic regions, adopting the SALSA (Search, Appraisal, Synthesis, and Analysis) framework in alignment with PRISMA guidelines to ensure methodological transparency and reproducibility. Nine peer-reviewed studies published between 2019 and 2024 were analyzed using qualitative coding and synthesis in NVivo. The findings identify thermal comfort, daylight, and circadian regulation as the most influential biophilic parameters, while greenery and water features, common in temperate frameworks, were limited due to environmental constraints. Key interventions include adaptive envelopes, optimized window design, intermediate buffer zones, and materials that balance insulation with sensory enrichment. The study proposes an "Interventions–Parameters–Outcomes" framework that illustrates the interrelationships among biophilic strategies, health-related outcomes, and climatic adaptation. While all studies originated from northern Canada, the conceptual framework provides a transferable foundation for future empirical validation and comparative research across diverse cold-climate regions, contributing to the advancement of climate-responsive, human-centered design in extreme environments.

Keywords: biophilic design; cold climate; Arctic; Sub-Arctic; health and well-being; systematic review

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1. Introduction

Biophilic design is grounded in the hypothesis that human beings possess an innate connection to nature and natural processes, and that fulfilling this connection promotes health and well-being in the environments we inhabit [1–4]. This human–nature connection has been linked to a wide range of psychological and physiological health benefits, including stress reduction, enhanced mood, lower blood pressure, pain reduction, decreased medication usage, faster recovery, and even lower mortality rates [5–11].

Although biophilic design is a relatively new discipline, researchers continue to refine its theoretical scope and develop comprehensive frameworks for its practical implementation. The main conceptual models have evolved through several major contributions.

Kellert, Heerwagen, and Mador [3] first proposed a structure with 72 parameters grouped into six categories. Later, Kellert & Calabrese [1] refined this into a more concise framework of 24 parameters across three groups, aiming to bridge the gap between theory and application. A further contribution came from Terrapin Bright Green [12], who proposed a framework with 14 parameters structured in three categories: *Nature in the Space*, *Natural Analogues*, and *Nature of the Space*. These frameworks guide the application of biophilic principles in the built environment using parameters such as visual and nonvisual connection with nature, materiality, biomorphic forms, and sensory variability.

Building on these precedents, Tekin et al. (2023) [13] proposed a framework specifically suited to architectural research, categorizing biophilic design parameters into two interrelated groups: Interventional Parameters, which refer to the physical elements and spatial interventions employed by designers, and Outcome Parameters, which encompass the perceptual and psychological responses that biophilic design seeks to foster to promote health and well-being. Although this framework distinguishes between the two categories, Tekin et al. (2023) emphasizes that biophilic design parameters are highly interconnected and that rigid boundaries cannot be clearly defined [13]. The present study investigates biophilic design parameters based on this dual structure.

However, critics argue that existing biophilic design frameworks remain too general to be effectively applied in practice. Despite their empirical grounding, they often lack specificity regarding building typologies, user profiles, and cultural or climatic contexts [14]. To address these limitations, recent scholarship advocates for a contextualized and user-centered approach to biophilic design. An effective framework should consider environmental and cultural factors alongside the specific requirements of the building type, user group, and climate. Only through such contextual precision and interdisciplinary integration can biophilic design fully support human health and well-being across diverse architectural settings [13–16]. In this regard, the present paper forms part of a broader research effort examining how biophilic design approaches vary across different climatic conditions.

This study aims to consolidate existing knowledge from biophilic design research and to inform human-centered policy and design practice by proposing a context-specific biophilic design guideline tailored to extreme cold climates, particularly the Arctic and Sub-Arctic regions. It presents a systematic review of scholarly literature that identifies, compares, and synthesizes biophilic design approaches while compiling critical recommendations for designing built environments that promote health and well-being under severe climatic constraints.

The Arctic and Sub-Arctic represent some of the most extreme and challenging environments on Earth, characterized by prolonged cold, substantial seasonal variation in daylight, and persistent snow and ice coverage. These conditions demand climate-responsive architectural strategies that address both environmental resilience and human well-being. The Arctic is generally defined as the area north of the tree line, encompassing tundra and polar deserts [17,18]. It is distinguished by extremely low mean annual temperatures, pronounced photoperiod extremes, and the high albedo effect of snow and ice surfaces [17,18]. Winter temperatures are exceptionally low, while summer temperatures rarely exceed 10 °C [19–21]. The Arctic experiences drastic photoperiod variation, with continuous daylight in summer and prolonged darkness in winter, affecting both ecosystems and human health [22,23]. Vegetation is sparse and dominated by mosses, lichens, dwarf shrubs, and grasses adapted to short growing seasons [24,25]. High winds and deep snow further complicate habitation and infrastructure development [18]. The Sub-Arctic, lying between 50° N and 70° N latitude, forms a transitional zone between boreal forests and tundra [20]. It exhibits strong climatic gradients, with July temperatures around 10 °C at its northern

boundary [18,21]. While photoperiod variation is less extreme than in the Arctic, it remains significant [21]. Snow cover is shorter-lived but still presents seasonal challenges [18]. Vegetation forms a mosaic of forest–tundra and southern tundra zones [20,23]. Both regions face environmental constraints such as extreme cold, high winds, and long winters that affect construction, transportation, and human health, particularly regarding circadian rhythm and psychological well-being. Climate change is intensifying these issues, especially in the Arctic, where warming is both rapid and pronounced [26].

Beyond temperature and wind, photoperiod emerges as a crucial design consideration. Extended daylight periods during Arctic and Sub-Arctic summers [27] have been linked to ecological and health impacts, including circadian disruption and UV-B overexposure [27–29]. These conditions require design strategies that moderate light exposure while preserving its health benefits. Architectural design in these regions must therefore respond to prolonged cold, seasonal light variation, permafrost conditions, and geographical remoteness. Such environments demand an approach that combines resilience, energy efficiency, and cultural sensitivity. Historically, the work of Ralph Erskine stands as a seminal reference in Arctic architecture. His designs were rooted in climatic adaptation and social inclusion, reflecting the needs of sparse northern communities [30]. Erskine's vision continues to influence current paradigms, now expanded by sustainability, equity, and climate resilience. Moreover, climate fundamentally shapes building performance, material selection, and environmental outcomes [31]. Cold-climate design strategies typically emphasize high-performance insulation, modular or relocatable structures, and the use of locally sourced materials, such as wood, to reduce transport costs and environmental impact [32,33]. Modular and prefabricated construction methods are also prevalent due to logistical constraints and short building seasons [34]. Sustainability remains central to contemporary Arctic architecture. Traditional vernacular techniques are being revisited to support carbon-neutral construction that meets modern performance standards [35]. For instance, free-running intermediate spaces provide energy-efficient transitions between indoor and outdoor environments in cold-climate housing. Architectural design in these regions must also navigate geological and climatic risks, ensuring structural stability and long-term performance amid shifting permafrost and severe weather [36]. Technological innovations such as external insulation wraps and mobile insulation systems help reduce energy loads in rigid structures [32]. Importantly, Arctic and Sub-Arctic architecture is not solely a technical challenge; it is also social and cultural. Inclusive design practices acknowledge local lifestyles, traditional knowledge, and Indigenous perspectives. In this sense, Arctic and Sub-Arctic architecture represents a convergence of environmental adaptation, technological innovation, and human-centered biophilic design, redefining how the built environment can promote health and well-being in some of the planet's harshest settings.

Therefore, this study employs a systematic review methodology to evaluate the current state of scholarly research on biophilic design in extreme cold climates (Arctic and Sub-Arctic). The review aims to identify key design strategies and their regional distinctions, and to develop evidence-based recommendations for both practitioners and future researchers. Accordingly, the study addresses the following research questions: What is the current state of biophilic design research in extremely cold climates? How do these findings differ from research conducted in temperate or moderate climate zones? What design recommendations can be made for architects working in Arctic and Sub-Arctic regions, and what directions should future research pursue?

2. Method

This study followed a systematic review methodology aligned with the SALSA (Search, Appraisal, Synthesis, and Analysis) framework and consistent with the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [37]. These frameworks were adopted to ensure methodological rigor, transparency, and reproducibility. The completed PRISMA 2020 checklist is provided in the Supplementary Materials.

A comprehensive and structured literature search was conducted across four academic databases used for the biophilic design discipline: Web of Science, Scopus, ScienceDirect, and EBSCOhost. The initial search, performed on 14 March 2024, used the Boolean syntax (*biophilic design*) *AND* (*climate*). Boolean search strings were applied consistently across all databases to ensure reproducibility and completeness of the evidence base. The search was limited to peer-reviewed journal articles published in English, excluding grey literature and non-peer-reviewed sources to maintain scholarly rigor. Studies were eligible for inclusion if they focused on biophilic design within architectural contexts. Studies were excluded if they originated from adjacent but distinct disciplines (e.g., urban studies, geography, or biophilic urbanism) or lacked a direct empirical or theoretical focus on biophilic architectural design.

The initial search yielded 380 articles, distributed as follows: Web of Science (48), Scopus (42), ScienceDirect (273), and EBSCOhost (17). After the removal of 46 duplicates, the remaining 334 records were screened at the title and abstract level. 39 articles were selected for full-text review, from which 8 studies met the inclusion criteria (Figure 1).

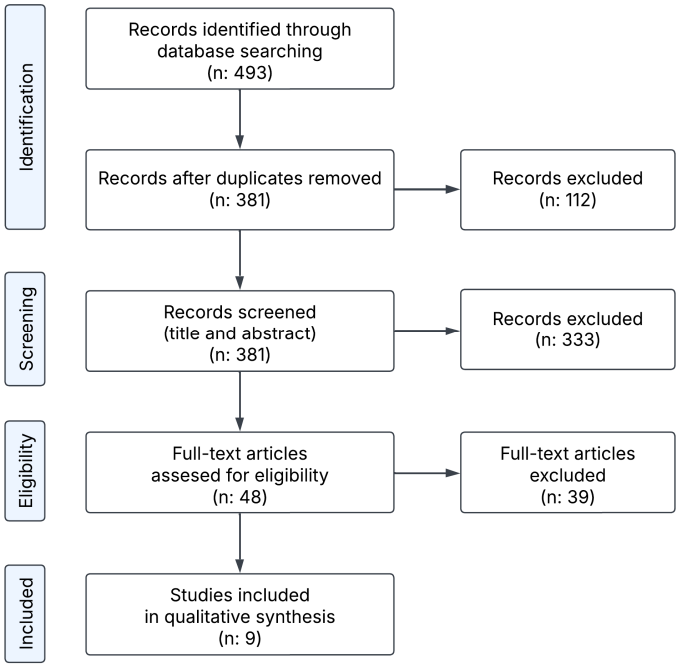


Figure 1. PRISMA flow diagram showing the identification, screening, eligibility, and inclusion stages of the literature search.

A second search was conducted on 4 May 2024, focusing on countries with published papers in Arctic and Sub-Arctic regions, including Canada, Sweden, Russia, Norway, Greenland, and Iceland. This round produced 86 additional articles (Scopus: 38; Web of Science: 41; EBSCOhost: 7). After abstract screening and duplicate removal, four full-text articles were reviewed, resulting in one additional study being included. To ensure currency, a third search was conducted in November 2024, restricted to studies published in 2024. The search terms used were: "*biophilic design*" *AND* (*cold OR Arctic OR Polar OR Northern*). This search retrieved 27 articles; however, no articles met the inclusion criteria.

All retrieved records (n = 496) were imported into Rayyan.ai (accessed on 19 October 2025), a semi-automated web-based platform designed to facilitate systematic reviews by expediting the screening of abstracts and titles [38]. Final decisions on inclusion were made through independent review, and a total of 9 documents are included in the study.

The methodological quality of the included studies was appraised using two complementary tools: the Scale for the Assessment of Narrative Review Articles (SANRA) [39] and the Mixed Methods Appraisal Tool (MMAT, 2018) [40]. SANRA was applied to assess conceptual and reporting quality in narrative or conceptual papers, focusing on the clarity of aims, scientific reasoning, literature coverage, and presentation. MMAT was used for empirical studies to evaluate methodological rigor across sampling, measurement validity, and analytical appropriateness. Overall, the nine included studies demonstrated consistently high quality. The narrative and conceptual papers (Studies 1, 2, and 6) achieved SANRA scores between 10–11/12, indicating strong rationale, coherent argumentation, and comprehensive referencing, though most lacked formal search strategies. The empirical and experimental studies (Studies 3–5, 7–9) scored 8–9/10 on MMAT and 11/12 on SANRA, reflecting robust methodological execution, valid and reproducible measurement procedures, and clear data presentation.

Collectively, the appraised evidence base can be characterized as methodologically rigorous and conceptually coherent, supporting the reliability of findings across both theoretical and empirical dimensions of biophilic and photobiological design research. The final dataset was imported into NVivo 14 for qualitative coding and thematic synthesis during the Synthesis and Analysis phases of the review.

2.1. Literature Review and Overview of the Studies

Following the Search and Appraisal phases of the systematic review, this subsection provides a critical overview of the nine studies that met the inclusion criteria. These studies, published between 2019 and 2024, collectively form the evidence base for the subsequent synthesis by summarizing their methodological orientations, research foci, and geographic contexts. All nine were conducted in Canada, with only one involving collaboration with the United States. The authors' primary affiliations span Architecture (9), Medicine (5), Electrical and Computer Engineering (5), and Mechanical Engineering (2). Notably, all publications on biophilic design in Arctic and Sub-Arctic climates originate from the Groupe de Recherche en Ambiances Physiques (GRAP) at Université Laval, Canada. While this concentration ensures methodological consistency, it also introduces a clear geographical and institutional bias, which limits the broader generalizability of the findings and underscores the need for comparative research in other cold regions.

Since the included studies employed various research methodologies (Table 1), the analysis and data extraction for this systematic review followed individualized procedures for each. The data collection methods of included studies ranged from on-site observations and post-occupancy evaluations to simulations, experimental procedures, numerical analyses, surveys, and literature reviews. This methodological diversity enhanced the overall quality, depth, and richness of the systematic review.

While two school-based studies investigated biophilic design parameters holistically, the remaining studies specialized in specific aspects of the built environment that are particularly critical in Arctic and Sub-Arctic climates, such as building envelopes, intermediate spaces, façades, window design, and lighting systems. This focused research approach provided valuable insights and design recommendations for individual components, which together inform a more comprehensive biophilic design framework for northern regions, the central aim of this study.

Table 1. General Overview of the Included Studies.

Study	Reference	Method/Approach	Focus/Context	Study Area	Climate
1	[41]	Qualitative scoping review and on-site observation	Examines façades, building envelopes, and intermediate spaces to establish a biophilic well-being framework for Arctic housing.	Cambridge Bay, Nunavut, Canada	Arctic/Polar Tundra
2	[42]	Mixed methods (literature review and lighting simulations)	Develops a photobiological approach to integrate daylight and circadian regulation in cold-climate buildings.	Northern Territories, Canada	Sub-Arctic/ Polar
3	[43]	Quantitative post-occupancy evaluation and simulation	Investigates spatial geometry, daylight access, and natural ventilation in biophilic school buildings.	Quebec, Canada	Sub-Arctic/ Hemiboreal
4	[44]	Experimental parametric simulation and numerical analysis	Tests photobiological and color-lighting configurations to support visual and circadian comfort during polar night.	Cambridge Bay, Nunavut, Canada	Arctic/Polar Tundra
5	[45]	Quantitative experiments and simulation analysis	Explores adaptive façade systems and shading-panel color/reflectance for biophilic and thermal performance.	Northern Territories, Canada	Sub-Arctic/ Polar
6	[46]	Qualitative narrative review and case analysis	Reviews biophilic school architecture, emphasizing indoor vegetation, materials, and daylighting strategies.	Quebec, Canada	Sub-Arctic/ Hemiboreal
7	[47]	Quantitative simulation study	Optimizes thermal, visual, and energy performance of intermediate spaces as biophilic buffer zones in Arctic housing.	Cambridge Bay, Nunavut, Canada	Arctic/Polar Tundra
8	[48]	Experimental laboratory analysis of lighting and surface color	Examines how correlated color temperature and surface hues affect circadian stimulation and spatial perception.	Northern Territories, Canada	Sub-Arctic/ Polar
9	[49]	Quantitative survey and simulation of daylighting	Analyzes window size, transparency ratios, and view quality to enhance circadian regulation and occupant well-being.	Cambridge Bay, Nunavut, Canada	Arctic/Polar Tundra

Note: All studies were conducted in northern regions of Canada, primarily affiliated with the Groupe de Recherche en Ambiances Physiques (GRAP) at Université Laval.

The final dataset comprised nine peer-reviewed studies published between 2019 and 2024, representing the entire body of empirical and conceptual research explicitly addressing biophilic architectural design in cold climates. Although the sample size is modest, it reflects the limited availability of scholarly work in this emerging area. A broader inclusion was not possible without compromising the study's focus and quality criteria. Each included study met rigorous methodological and conceptual standards, providing a representative and reliable evidence base for synthesizing design strategies in Arctic and Sub-Arctic regions.

Collectively, the nine studies reveal several consistent research patterns. Most adopt mixed-method or simulation-based approaches focusing on building envelopes, lighting,

and thermal adaptation, core challenges in cold-climate architecture. Two studies address educational facilities, while others examine housing and experimental prototypes. Despite their shared Canadian context, the studies encompass diverse methodological orientations and scales of analysis, offering a sufficiently heterogeneous basis for meta-synthesis. This body of evidence, therefore, captures the current state of knowledge on biophilic design in extreme cold climates and identifies clear gaps for future comparative research in other regions.

Although all studies were conducted in Canada, their case locations vary geographically. To provide contextual insight into climatic variation, Figure 2 compares daylight duration and thermal patterns between Québec City (Sub-Arctic) and Cambridge Bay (Arctic). Québec City experiences moderate seasonal variation, with daylight ranging from about 8 to 16 h and temperatures from −20 °C in winter to around 30 °C in summer. In contrast, Cambridge Bay exhibits extreme seasonal shifts, with 24 h daylight in summer and near-total darkness in winter. Temperatures in Cambridge Bay are considerably colder, reaching nearly −40 °C in winter and only slightly above 10 °C in summer.

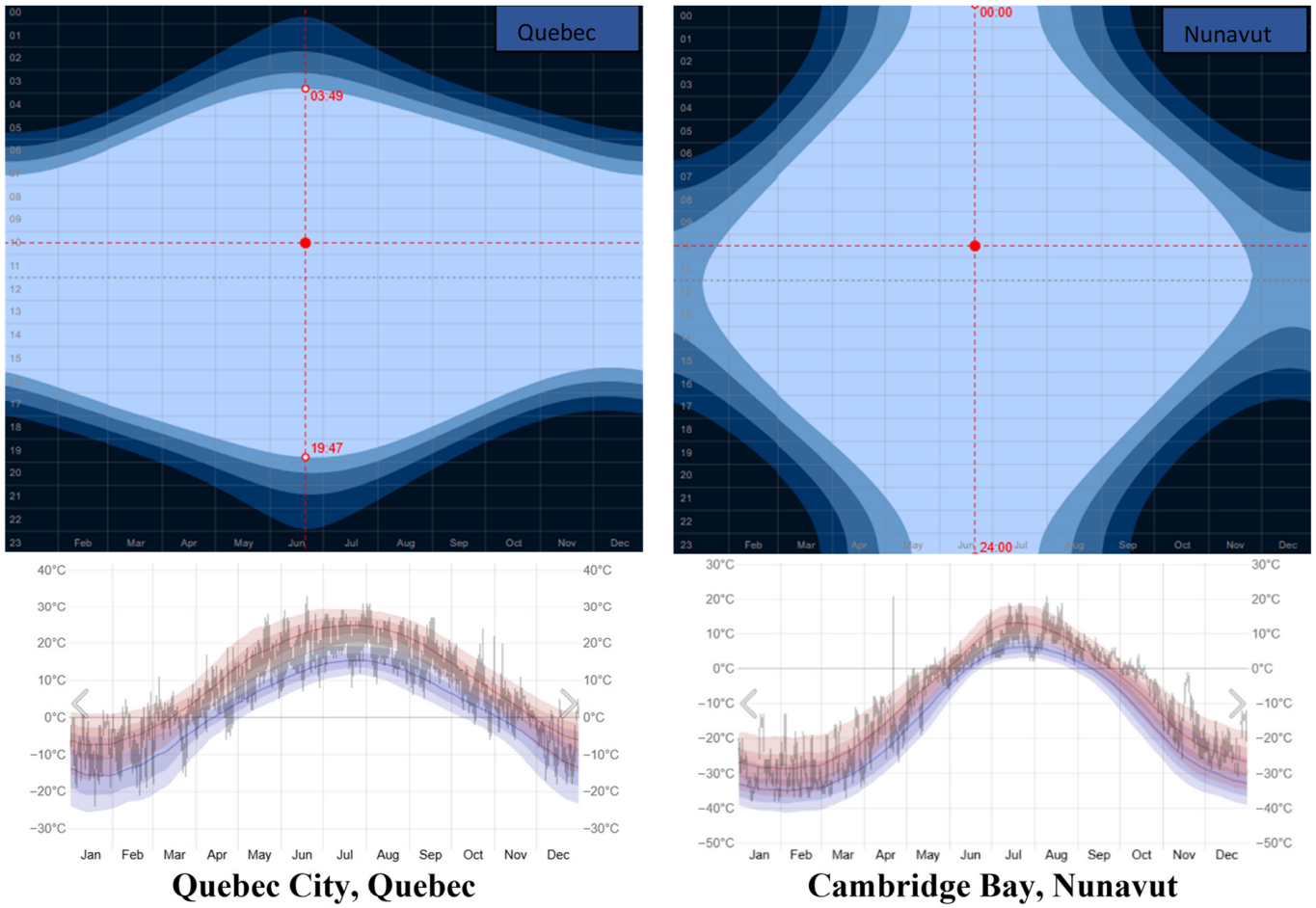


Figure 2. Day-length and annual temperature range graphs for Quebec City and Cambridge Bay (Day-length chart produced using the Sunpath app at andrewmarsh.com (accessed on 19 October 2025); Annual temperature range data © WeatherSpark.com (accessed on 19 October 2025)).

This comparison highlights how photoperiod and thermal contrasts intensify with latitude. Although Québec City lies at the southern edge of the Sub-Arctic zone, it still experiences prolonged summer daylight, over 16 h, which increases UV exposure. Conversely, its shorter winter days result in extended darkness, though less severe than in Arctic settlements farther north. These pronounced seasonal photoperiod patterns, characterized

by intense summer light and prolonged winter darkness, were critically considered when analyzing the selected studies, as they directly inform biophilic design needs and strategies in cold-climate architecture.

2.2. Data-Analysis Procedure

During the Analysis phase of the SALSA framework, the nine included studies were imported into NVivo 14 for qualitative synthesis. An open-coding, inductive approach was applied, in which codes were manually identified while reviewing each full text. These codes captured relationships among biophilic design parameters, architectural interventions used in Arctic and Sub-Arctic climates, and their effects on human health and well-being.

To guide coding consistency, this analysis adopted the conceptual model developed by Tekin et al. (2023), which organizes biophilic design parameters into two interrelated groups (Table 2) [13]:

- Interventional Parameters: the physical or spatial elements and design interventions implemented by architects, and
- Outcome Parameters: the perceptual, psychological, and behavioral responses that biophilic design aims to evoke.

Table 2. Biophilic design framework based on interventions and outcomes.

Interventional Parameters	Outcome Parameters
Air-Ventilation	Curiosity
Biophilic Design Architectural Form, Layout, Furnishing and Fittings	Circadian Rhythm
Bringing Outside to Inside	Perception by Personal Past-Sense of Belonging
Colour	Refuge—Feeling Safe
Fire	Socialising
Greenery—Plants	View—Prospect
Light—Daylight	Welcoming—Relaxing
Material	Perception by Gender
Multi-Sensory Experience -Auditory Experience -Olfactory Experience -Tactile Experience	Risk
Seasonal Changes	
Spaciousness	
Thermal Comfort-Variability	
Water	

Although these categories provide analytical clarity, the framework emphasizes that the parameters are inherently interconnected and that rigid boundaries between them cannot be strictly defined. This dual structure informed the coding hierarchy in NVivo and supported the identification of cause-and-effect links between architectural strategies and user-centered outcomes in cold-climate contexts.

NVivo 14 software facilitated the organization, visualization, and quantification of these codes, enabling identification of interconnections, comparison of recommendations across studies, and prioritization of themes. The analytical process was partly deductive,

drawing on biophilia theory and the Tekin et al. framework, and partly inductive, allowing new climate-specific insights to refine the theory. The resulting code structure formed the empirical basis for the meta-synthesis presented in the following Section 3.

3. Results

3.1. Overview of Coded Themes

The qualitative analysis of the nine studies revealed strong convergence in the treatment of thermal comfort and light as dominant biophilic design parameters. All studies prioritized thermal adaptation to extreme cold conditions, while daylight management and photoperiod balance emerged as the second most emphasized theme. In contrast, parameters commonly highlighted in temperate-climate research, such as greenery and water, were less frequently addressed because of environmental constraints. For instance, greenery was considered in only two studies (Studies 3 and 6), and water elements were mentioned solely in Study 6. Table 3 summarizes the contribution of each study to the coding matrix. It lists the presence of biophilic design parameters and architectural interventions identified through qualitative synthesis.

Table 3. Contribution of the studies for data analysis.

		Study 1	**Study 2**	**Study 3**	**Study 4**	**Study 5**	**Study 6**	**Study 7**	**Study 8**	**Study 9**
BIOPHILIC DESIGN PARAMETERS	Thermal Comfort-Variability	x	x	x	x	x	x	x	x	x
	Light	x	x	x	x	x	x	x	x	x
	View	x	x	x			x			x
	Material					x	x	x	x	x
	Ventilation—Fresh Air	x	x	x			x			
	Colour				x	x			x	
	Indoor-Outdoor Connection	x	x			x				
	Greenery			x			x			
	Open Spaces—Outdoor						x			
	Traditional Attachment		x							
	Water						x			
INTERVENTIONS	Window	x		x		x	x	x		x
	Architectural Form	x	x	x		x				
	Intermediate Space	x				x	x	x		
	Artificial Lighting Design		x		x				x	
	Adaptive Envelope		x	x		x				
	Shading Systems	x				x				

3.2. Pattern Frequency and Interconnections

The coded dataset revealed extensive interrelationships among parameters and interventions. Figure 3 visualizes the frequency of each parameter and its co-occurrence with others. Thermal comfort was omitted from this visualization because of its dominant frequency, which obscured other relationships. The network highlights the central role and mutual reinforcement of light, view, fresh air, window design, and adaptive building envelopes in Arctic and Sub-Arctic architecture.

These results demonstrate that successful cold-climate biophilic design relies on the interplay between environmental control and sensory connection. Lighting strategies and envelope adaptations compensate for limited daylight, while intermediate spaces and operable windows mediate thermal transitions and improve perceived comfort.

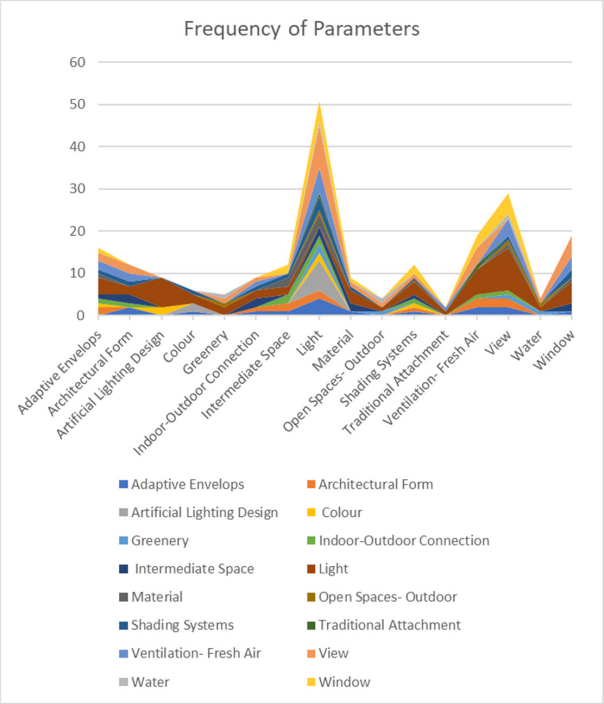


Figure 3. Frequency and co-occurrence of coded parameters and interventions (thermal comfort excluded for clarity).

3.3. Synthesized Recommendations from Included Studies

Before conducting the meta-synthesis, all design recommendations were extracted from the primary studies. Table 4 consolidates these recommendations, reflecting the key strategies adapted for Arctic and Sub-Arctic contexts and their implications for human health, well-being, and environmental responsiveness. These synthesized findings directly informed the development of the climate-specific conceptual framework presented in the subsequent Section 4.

Table 4. Summary of Recommendations Synthesized from the Nine Studies.

Study 1	**Intermediate Spaces**	
	Thermal Adaptation Zones	Use vestibules, porches, and lobbies as thermal buffer zones to gradually transition occupants between indoor and outdoor environments, improving comfort and safety. Equip these spaces with daylighting control systems to regulate light exposure, helping occupants adapt to extreme seasonal light variations. Design intermediate spaces to strengthen visual and sensory connections to nature, supporting outdoor interaction through seasonal adaptability. These spaces should also help reduce heat loss, improve energy efficiency, and protect windows and doors from harsh conditions.
	Building Layout and Façades	Arctic buildings should incorporate thermal adaptation zones into their layouts, spatial organization, and openings, ensuring they align with how spaces are used and occupants' activities.
	Window Design, Air Quality and Daylight Control	
	Window Size	Redesign windows to balance energy efficiency and daylight access, increasing window size where feasible to improve natural light and outdoor views.
	Shading Systems	Introduce exterior shading systems to control excess daylight during polar summers and to prevent snow buildup in winter, reducing glare and thermal imbalance.
	Indoor Air Quality	Address poor indoor air quality caused by airtight construction, lack of mechanical ventilation, non-operable windows, and moisture buildup.
	Photobiological Adaptation	
		Support photobiological adaptation by aligning indoor-outdoor light exposure with seasonal daylight patterns and local photoperiods, helping maintain circadian rhythms and promoting visual comfort.

Table 4. *Cont.*

Study 2	**Balance Thermal Comfort with Nature Connection**	
		Balance thermal comfort with nature connection by ensuring buildings provide daylight access and views to nature, reducing reliance on artificial lighting and mechanical heating.
	Daylight, View, and Lighting Design	
	Natural Light with Views to Nature	Develop lighting scenarios aligned with local photoperiods, and combine natural light exposure with outdoor views in both lighting design and architectural planning to support circadian health, particularly in indoor environments where occupants spend most of their time.
	Integrate IF and NIF Effects into Lighting Design	Lighting design should balance Image-Forming (IF) effects (visual comfort) with Non-Image-Forming (NIF) effects (circadian health and mood regulation), especially in regions with extreme seasonal daylight shifts.
	Incorporate Light Spectrum Variation	Use both blue-enriched and red-enriched lighting to boost alertness and improve cognitive performance
	Adaptive Building Envelopes	
		Develop adaptive building envelopes that respond to seasonal and hourly changes, providing daylight, thermal comfort, and visual connection to the outdoors, while also supporting circadian health through tailored light exposure.
Study 3	**Building Form and Geometry**	
	Building Form	In cold climates, thin buildings provide better natural light, fresh air, and outdoor views compared to compact buildings, which are often prioritized for energy efficiency. Certain linear building geometries can achieve similar energy performance to compact forms, while offering improved daylight and ventilation.
	Architectural Offsets	Architectural offsets can be used to increase daylight access by identifying zones closer to the perimeter with greater daylight and nature connection potential.
	Window Design	
	Window Size and Placement	Window size and placement should be carefully planned to optimize sunlight, fresh air, and outdoor views, which are critical for biophilic experiences.
	Glazing Ratios	Glazing ratios between 10% and 25% offer a good balance between daylighting, thermal comfort, and energy efficiency, minimizing heat loss in winter and overheating in summer.
	Operable Windows	Operable windows enhance biophilic qualities by enabling thermal, olfactory, and auditory exchanges with the outdoor environment, fostering a stronger connection to nature.
	Greenery and Landscape Integration	
		Planting deciduous trees near building facades provides shade in summer and allows sunlight in winter, enhancing thermal comfort. This also allows occupants to experience seasonal changes, supports biodiversity, and improves air quality, enriching biophilic engagement.
	Building Envelope as a Biophilic Interface	
		In cold climates, the building envelope is crucial for enhancing connections to nature, influencing daylight access, natural ventilation, views of outdoor vegetation.
Study 4	**Electrical Lighting and Colour Configuration**	
	Adaptive Lighting Systems	Use adaptive lighting systems that adjust to the time of day and activity needs, especially where natural daylight is limited.
	Different Light Positions and Surface Colors	Combine side, zenithal, and frontal lighting with different surface colors to support both visual comfort and circadian health. Prioritize zenithal lighting for morning alertness and coordinate light color temperatures with surface materials to enhance both visual and biological responses.
	Coordinate Light Color Temperature with Surface Colors	The color temperature of light directly influences both visual perception and circadian rhythms, particularly when combined with reflective surfaces, making careful coordination between lighting and materials essential.
	Sensory-Rich Spaces	Use varied lighting and color strategies to create diverse, sensory-rich spaces that strengthen connections to natural light rhythms, particularly in northern climates.

Table 4. *Cont.*

Study 5	**Adaptive Shading Panels**	
	Dynamic Systems	Incorporate rotating or flipping shading panels that can adapt to extreme daylight variations across different times of day and seasons, optimizing both visual comfort and circadian stimulation while enhancing sensory connections to nature.
	Colour	Use cool colours to increase circadian stimulation, and warm colours to enhance photopic light levels and visual comfort, and create warmer light. Combine panel colours and positions to balance visual and biological needs.
	Reflectance	Matt panels have a greater effect on both melanopic and photopic light levels than semi-glossy panels, making them more effective for biophilic and photobiological benefits.
	Orientation and Inclination	Horizontal panels and upward inclinations have a greater impact on circadian health than other orientations. Vertical panels with two different colors on each side can further enhance light variability, contributing to the visual interest and dynamic indoor environments.
	Intermediate Spaces	
	Window-to-wall Ratio	Adopt a 60% window-to-wall ratio (compared to Canada's 20% standard) to enhance biophilic connections by improving views and daylight access.
	Buffer Zones	Combine larger windows with intermediate thermal buffer spaces to create gradual, adaptable transitions between indoor and outdoor environments, improving nature connection, thermal comfort, and biological responses.
Study 6	**Indoor Natural Elements**	
	Maximize Natural Elements Indoors	As people in cold climates spend most of the year indoors, daylight, nature views, and indoor greenery should be maximized to support well-being.
	Indoor Vegetation	Indoor vegetation enhances cognitive performance, air quality, and psychological comfort, though its impact varies based on occupant interaction.
	Materials	Natural materials, such as wood, contribute to aesthetic, sensory enrichment, and emotional well-being.
	Microclimatic Design	
	Outdoor Comfort	Microclimatic strategies can extend outdoor usability by up to six weeks, making outdoor spaces more accessible in colder months. Reduce wind exposure by adjusting site geometry, using vegetation, and placing snowdrifts. Moderate local climate conditions by including water features. Provide sheltered outdoor spaces to enhance thermal comfort.
	Daylight Access and Visual Connections to Nature	
	Window Size	Large windows with optimal orientation can maximize daylight penetration and visual access to nature.
	Reflective Surfaces	Reflective surfaces (e.g., light furniture, reflective ceilings, bright interiors) should be integrated to enhance daylight distribution, particularly during dark winter months.
	Adjustable Blinds	Adjustable blinds to regulate glare and daylight exposure.
	Balance Natural and Mechanical Ventilation	
	Hybrid ventilation strategies	Natural ventilation improves air quality and sensory variation, but its effectiveness is limited in cold climates due to heat loss concerns. Hybrid ventilation strategies, combining mechanical and natural airflow, help maintain healthy indoor air quality while supporting biophilic principles.
	Operable Windows	Operable windows enhance biophilic connections by introducing natural airflow, but their efficiency depends on building orientation, microclimate conditions, and noise pollution levels.
	Transition Spaces	
		Vestibules, covered outdoor areas, and enclosed courtyards can function as thermal buffer zones, easing the transition between cold outdoor and warm indoor spaces.

Table 4. *Cont.*

Study 7	**Daylight Access**	
	Space Configuration and Transparency	Transparent facades and roofs maximize daylight absorption while maintaining biophilic connections with the outdoor environment. The optimal design includes 6–7 m in depth and 50–80% transparency, ensuring sufficient daylight penetration while maintaining thermal efficiency.
	Prevent Glare	Solutions such as blinds, movable seating, and flexible scheduling should be implemented.
	Orientation	North-facing intermediate spaces reduce peak energy demand
	Natural Ventilation	
	Operable windows	Enhance natural airflow and air quality. Opening side windows can prevent overheating, extending the usable hours of intermediate spaces by up to 15 h per summer day.
	Materials	
	Polycarbonate	Polycarbonate sheets offer better insulation than glass, maintaining stable indoor temperatures year-round.
Study 8	**Optimize Lighting**	
	Color Temperature (CCT)	Cooler lighting (6500 K) enhances alertness, while warmer lighting (2700 K) promotes relaxation. CCT above 6500 K does not always enhance circadian stimulation—warmer tones may be more effective in some cases.
	Lighting Design	Lighting design should balance CCT, intensity, and distribution, particularly where natural daylight is scarce.
	Surface Colours	
		Blue and green surfaces (85% coverage at 6500 K) increase melanopic and photopic lux levels, supporting biological rhythms. Red surfaces (85% coverage) produce the lowest EML levels, requiring extra artificial lighting. Neutral colors lower CCT, altering the lighting ambiance.
	Material Finishes	
	Reflective and colored	Reflective and colored surfaces optimize daylight use, reducing the need for artificial lighting.
	Glossy vs. Matte	Glossy finishes reflect light, improving brightness and indoor-outdoor connections. Matte finishes reduce glare and define spatial boundaries.
Study 9	**Window Design**	
	Daylight	Areas near windows provide the highest exposure to natural light, making them the most health-supportive indoor spaces. Larger, well-oriented windows improve daylight uniformity and maintain consistent Equivalent Melanopic Lux (EML) levels, essential for circadian regulation and well-being.
	Circadian Stimulation	Proper window placement reduces reliance on artificial lighting while enhancing circadian stimulation and occupant comfort. The distance from windows significantly impacts EML intensity and global luminance, influencing both visual comfort and biological rhythms.
	Transparency	Transparency ratios must be optimized to balance daylight access, thermal performance, and outdoor visibility.
	Views	Design windows to provide unobstructed views of nature, reducing stress and improving well-being. Use visual simulations to refine daylight strategies and energy efficiency.

3.4. Summary of Results

Overall, the meta-synthesis indicates that biophilic design in extreme cold climates is driven primarily by thermal regulation, daylight access, and circadian alignment. Building components such as windows, adaptive envelopes, and intermediate buffer spaces serve as crucial mediators between interior comfort and harsh outdoor conditions. Elements commonly associated with temperate environments, such as greenery, water, and multisensory features, were found to be secondary, often replaced by light and material strategies that simulate or substitute natural experiences. These results establish the empirical basis for the conceptual framework and discussion that follow.

4. Discussion

4.1. Interpreting the Meta-Synthesis

Biophilic design in Arctic and Sub-Arctic climates converges on three drivers: thermal comfort, daylight access, and circadian regulation. In contrast with temperate settings, where greenery and water often dominate, cold-climate practice relies on mediated connections to nature through light, materiality, enclosure, and carefully managed exchanges with the outdoors. Across all nine studies, thermal adaptation was a universal priority; light management and photoperiod alignment emerged as the second, reflecting long winter darkness and prolonged summer daylight.

A consistent theme is the need to rebalance contemporary envelopes, optimized for insulation and airtightness, so they also support sensory richness, daylight, and circadian cues. Traditional northern precedents suggest this balance is possible when spatial transitions and diurnal/seasonal rhythms are designed intentionally. Where those cues are absent, reliance on mechanical systems increases and risks circadian disruption and mood and sleep disturbances (Study 2)

4.2. Lighting Design and Circadian Cycle

Lighting design in northern and Sub-Arctic regions should carefully address both Image-Forming (IF) effects, which influence visual comfort, brightness, and glare, and Non-Image-Forming (NIF) effects, which affect circadian rhythms, mood regulation, and biological health. Both aspects must be balanced, particularly in extreme environments where seasonal variations in daylight are pronounced.

Recognizing these challenges, existing Arctic buildings often require redesign or adaptation to improve indoor–outdoor transitions. This involves ensuring healthy indoor air quality, providing enhanced access to natural light while minimizing heat loss and glare, and ultimately balancing occupant well-being with energy efficiency, especially in remote, off-grid communities (Study 1).

The prolonged winter nights characteristic of northern regions necessitate careful consideration of artificial lighting to enhance the biophilic value of indoor spaces while maintaining adequate circadian stimulation for health and well-being. In this context, Study 8 proposed a series of recommendations based on experimental findings. It emphasizes that lighting, shading, and color strategies should be integrated to enhance spatial experience and occupant well-being, particularly in northern latitudes, where extended periods of indoor activity during winter require adaptive lighting conditions to meet physiological and psychological needs.

To further support circadian health and biophilic experience, it is essential to integrate views of outdoor nature into both lighting design and architectural planning. Combining natural light exposure with access to outdoor views is especially important in environments where people spend most of their time indoors. Accordingly, Study 2 recommends developing lighting scenarios that align with the local photoperiod, ensuring sufficient exposure to daylight and visual connection with outdoor environments. Such measures are critical for sustaining healthy circadian rhythms and promoting overall well-being.

4.3. Artificial Lighting

In northern climates, biophilic design should incorporate adaptive lighting systems that respond to the time of day and the nature of activities, particularly in environments with limited natural daylight. Studies 2, 4, and 8 recommend artificial lighting strategies to regulate the circadian cycle during winter, when prolonged nighttime affects northern regions.

For example, Study 4 demonstrates that designers can create indoor environments supporting both visual tasks (Image-Forming effects) and circadian health (Non-Image-Forming effects) by combining different luminaire positions, such as side, zenithal, and frontal lighting, with diverse surface color configurations. The position of light sources significantly influences both visual comfort and circadian stimulation. Accordingly, Study 4 reports that zenithal lighting is more effective for morning alertness than frontal lighting, which may fail to achieve minimum circadian stimulation thresholds.

Study 8 confirms that correlated color temperature (CCT) strongly affects alertness and relaxation. Cooler lighting enhances alertness, whereas warmer lighting promotes relaxation. Blue-enriched light improves mood, increases alertness, and reduces fatigue (Studies 4, 5, and 8). However, neutral white light (≈4000 K) is generally preferred for comfort over warm light (≈2700 K).

CCT also plays a key role in influencing circadian rhythms and visual comfort. Higher CCTs (≈6500 K) increase melanopic stimulation and promote alertness, while lower CCTs (≈2700 K) reduce stimulation, supporting relaxation. Light intensity and color distribution further influence brightness perception and overall comfort (Study 8). Findings from Study 8 indicate that 89% of tested scenarios achieved the recommended Equivalent Melanopic Lux (EML) threshold of 275 EML, which supports circadian synchronization. Interestingly, CCTs above 6500 K do not necessarily yield stronger circadian stimulation; in some cases, warmer tones may be more effective. Therefore, to optimize circadian health, lighting design in northern climates with limited daylight should carefully balance CCT, intensity, and distribution.

The color temperature of light sources also plays a critical role in both visual and non-visual responses, influencing the circadian cycle and spatial perception, particularly in interiors with reflective surfaces. Consequently, coordinating lighting design with surface materials is essential to maximize both photopic and melanopic responses (Study 4).

4.4. Color as a Photobiological Tool

In Arctic and Sub-Arctic regions, where prolonged winter nights necessitate artificial lighting, color selection must complement dynamic lighting systems. Integrating varied lighting strategies with diverse surface colors enables spatial diversity and maintains essential biological and visual light levels (Studies 4 and 8). This approach enhances biophilic experiences, supports sensory enrichment, and improves well-being in daylight-deprived environments (Study 4).

Studies 4, 5, and 8 highlight that color selection plays an important role in enhancing visual comfort, supporting circadian health, and improving spatial experience. Color influences both melanopic and photopic light levels, affecting alertness, biological rhythms, and overall well-being (Studies 5 and 8). Experiments involving shading panels in Sub-Arctic conditions show that cool colors, such as light blue, strong blue, green, and cool white, increase melanopic light levels, enhancing circadian stimulation and alertness. Among these, light blue panels have the strongest effect, particularly under neutral or cool outdoor lighting conditions (Study 5). In contrast, warm colors, including strong yellow, yellow-green, strong red, and warm white, increase photopic light levels for visual tasks while lowering color temperature, creating a warmer and more calming indoor environment (Study 5).

Study 8 further emphasizes that surface color and material finish impact lighting, circadian health, and spatial perception. Blue and green surfaces with approximately 85% coverage at 6500 K effectively regulate melanopic and photopic lux levels, supporting biological rhythms. In contrast, red surfaces with similar coverage produce the low-

est Equivalent Melanopic Lux (EML) levels, requiring supplemental artificial lighting (Study 8).

4.5. Materials and Sensory Comfort

Material selection plays a crucial role in optimizing daylight, thermal comfort, and overall well-being in indoor environments in Arctic and Sub-Arctic climates. To enhance indoor environmental quality, materials should balance insulation, light distribution, and sensory comfort while addressing the challenge of limited daylight during winter months.

Reflective surfaces are essential for maximizing natural light during dark winter periods. Study 6 recommends integrating light-colored furniture, reflective ceilings, and bright interior finishes to enhance daylight distribution and reduce reliance on artificial lighting. Additionally, Study 8 highlights that glossy finishes improve brightness and strengthen indoor–outdoor connections by reflecting light, whereas matte finishes reduce glare and sharpen spatial boundaries. However, Study 5 notes that matte panels have a greater influence on melanopic and photopic light levels than semi-gloss panels of the same color. This suggests that matte surfaces can enhance circadian stimulation and overall lighting quality, particularly in spaces with limited daylight exposure.

Material choice is also key to maintaining a stable indoor temperature in cold climates. Study 7 found that polycarbonate sheets provide better insulation than glass, contributing to thermal efficiency while ensuring consistent daylight penetration. The balance between thermal performance and daylight access can be further optimized by adjusting transparency ratios between 50% and 80%, ensuring sufficient natural light without excessive heat loss or glare.

Furthermore, natural materials, such as wood, contribute to psychological comfort, sensory enrichment, and aesthetic warmth (Study 6). The use of wood in interior spaces creates a welcoming atmosphere while complementing daylighting strategies by softening contrasts and enhancing spatial perception.

By integrating reflective surfaces, natural materials, and carefully calibrated transparency levels, architects can create energy-efficient, well-lit, and comfortable spaces suited to the unique challenges of cold climates.

4.6. Window Design: Daylight, View, and Air

Findings from the reviewed studies consistently show that window design in cold climates plays an essential role in balancing daylight access, thermal performance, and indoor air quality, while also fostering crucial biophilic connections to nature (Studies 1, 3, 5–7, and 9). Given the seasonal fluctuations in daylight availability, strategic window placement, size, and operability are essential for maintaining occupant well-being, energy efficiency, and visual comfort (Study 5).

Windows are critical for daylight penetration, particularly in Arctic regions where natural light varies significantly between seasons. Larger, well-oriented windows provide higher exposure to daylight, supporting circadian health and psychological well-being (Study 9). However, transparency ratios should be carefully balanced, ideally between 10% and 25%, to ensure adequate daylight while preventing heat loss in winter and overheating in summer (Studies 3 and 9). Additionally, glazing properties should be optimized to regulate light intensity, improve visual comfort, and reduce reliance on artificial lighting (Study 9).

To achieve a balanced indoor environment, window size and placement must be carefully assessed. Glazing should prevent unwanted heat loss during winter while still allowing adequate daylighting (Study 3). Well-positioned windows with optimal orienta-

tion can ensure uniform daylight distribution, reducing dependence on artificial lighting (Study 9).

In cold climates, windows influence both indoor temperature regulation and occupant comfort. Operable windows enhance natural ventilation, improving air quality while supporting thermal adaptation (Studies 6 and 7). However, their effectiveness depends on building orientation, microclimate conditions, and noise levels (Study 6). Opening windows can significantly reduce overheating during summer, extending the usability of intermediate spaces by up to 15 h per day (Study 7). To maintain thermal comfort, adjustable blinds and shading systems that preserve visual connection, along with intermediate spaces, help mitigate excessive heat gain or loss (Studies 1 and 6). Furthermore, adaptive shading panels with adjustable orientation and reflectance offer flexible solutions for managing solar gain and daylight (Study 5).

Despite well-maintained indoor temperatures, many Arctic buildings suffer from poor indoor air quality due to high airtightness, moisture buildup, and limited ventilation (Study 1). Non-operable windows exacerbate this issue by restricting fresh air circulation and natural thermal variability. Incorporating operable windows into intermediate spaces can enhance airflow and temperature regulation, creating a healthier indoor environment (Studies 1, 3, 6, and 7). The positioning of windows, at the top or bottom of walls, also affects air circulation efficiency, improving ventilation performance (Study 5).

Windows also provide views of natural outdoor settings, an essential biophilic element that reinforces mental well-being and reduces stress (Studies 2, 3, 6, and 9). However, existing Arctic buildings often feature small windows due to strict energy regulations, restricting both natural light and outdoor views (Study 1). This issue can be addressed by adjusting window placement and increasing transparency ratios where feasible.

4.7. Ventilation and Air Quality

Many Arctic buildings experience poor indoor air quality despite having adequate heating systems. This issue is primarily due to high airtightness, the absence of mechanical ventilation, non-operable windows, and condensation buildup on cold surfaces (Study 1). These conditions lead to moisture retention, increased pollutants, and overall discomfort, negatively impacting occupant health and well-being. Natural ventilation, strongly encouraged in biophilic design, improves air quality and strengthens biophilic connections by allowing fresh airflow and natural temperature variation. Properly positioned operable windows enhance ventilation, sensory experiences, and temperature regulation while maintaining thermal efficiency (Studies 1–3, and 6).

Maintaining good air quality and effective ventilation in cold climates can be challenging due to thermal discomfort, heat loss, and airtight construction. While natural ventilation provides health and sensory benefits, its use is limited during harsh winter conditions (Study 6). Study 6, therefore, proposes a balanced ventilation strategy that integrates both mechanical and natural airflow to sustain healthy indoor environments while supporting biophilic design principles. Mechanical systems ensure consistent ventilation, whereas operable windows can be used strategically for fresh-air exchange when outdoor temperatures permit. This balance reduces dependence on artificial heating and fosters dynamic airflow patterns that support well-being and thermal comfort.

Building form also affects ventilation and daylighting. Findings from Study 3 show that thin building forms allow better air and daylight penetration, whereas compact forms improve energy efficiency [50]. Some linear geometries can achieve comparable energy performance while improving ventilation. Offsetting building perimeters can further enhance natural airflow and daylight exposure while reducing reliance on mechanical systems (Study 3).

4.8. Building Envelopes

Studies 2, 3, and 5 emphasize that building envelopes are essential for regulating ventilation, daylight access, thermal comfort, and air quality, while enhancing biophilic connections through seamless indoor–outdoor transitions. Study 2 concludes:

> "This paper calls special attention to building envelopes and adaptation strategies as a promising hypothesis to address the challenges of biophilic design for northern regions."

Study 5 integrates adjustable shading panels into building envelopes to accommodate seasonal variations in daylight and temperature. These panels can rotate or flip to optimize visual comfort and circadian stimulation. Their adaptability strengthens biophilic connections by modulating sensory interaction between interior and exterior environments. Panels can be adjusted based on color spectrum (cool to warm tones), reflectance (matte or semi-gloss finish), orientation (horizontal or vertical), inclination (upward, downward, or tilted), positioning (top or bottom near windows), and size or density (Study 5). This customization enables precise control of natural light exposure, glare reduction, and energy performance while providing psychological and physiological benefits (Studies 3 and 5).

The color spectrum of shading panels strongly influences circadian rhythms and visual comfort in Sub-Arctic photoperiods. Cool colors (light/strong blue, green, cool white) increase melanopic light levels and alertness, whereas warm colors (yellow, red, warm white) increase photopic light levels, aiding visual tasks and creating a warmer ambiance (Study 5). Strategically positioning colors, cool at the top, warm at the bottom, can balance circadian support with visual comfort, creating healthier, adaptable interiors (Study 5).

Well-designed envelopes in Arctic regions should provide biophilic experiences by maximizing natural light and outdoor views, reducing reliance on artificial lighting (Study 2). Strategic glazing ratios of 10–25% ensure sufficient daylighting while minimizing heat loss in winter and overheating in summer (Study 3). Envelopes must also adapt to seasonal and hourly climate variation, maintaining energy efficiency [51] and occupant comfort (Study 2), while improving ventilation and reducing condensation in sealed Arctic buildings (Study 3).

4.9. Intermediate Spaces

The adaptive envelope proposed in Study 5 includes intermediate thermal buffer spaces and efficient window-to-wall ratios to enhance both biophilic and photobiological quality. Compared with Canada's standard 20% window-to-wall ratio, the proposed 60% ratio provides stronger outdoor connection. Combining larger windows with controllable intermediate spaces creates sequential, adaptable transitions between indoor and outdoor environments, improving nature connection, biological response, and thermal comfort in extreme cold conditions. Intermediate spaces are widely recognized as key to improving comfort and biophilic value in cold climates (Studies 1, 5–7):

> "At the same time, the spaces must also promote the well-being and cultural needs of the occupants. Architectural configurations of biophilic intermediate spaces must be optimized to establish a thermal adaptation zone for the occupants, maximize daylight within the space, and improve the energy efficiency of the housing units." (Study 7, p. 6).

Intermediate spaces function as thermal buffer zones, regulating indoor–outdoor transitions and reinforcing biophilic connection. Examples include vestibules, enclosed courtyards, and covered outdoor areas that minimize heat loss, improve thermal comfort,

and extend safe exposure to natural elements, thereby enhancing well-being and energy efficiency (Studies 1, 6, and 7).

Such spaces should feature transparent façades and roofs to maximize daylight absorption, support circadian health, and improve thermal conditions on sunny days (Studies 1 and 7). However, excessive transparency may cause glare, mitigated by blinds, movable seating, or flexible scheduling (Study 7). The most efficient design includes a depth of 6–7 m and transparency between 50–80%, providing adequate daylight while preserving thermal performance. Energy-efficient intermediate spaces can reduce overall consumption by ≈17%, with maximum benefits in north-facing configurations (Study 7). Material-wise, polycarbonate sheets outperform glass for insulation while maintaining daylight; reflective and colored surfaces help distribute light efficiently, reducing glare and enhancing comfort (Study 1).

4.10. Microclimatic Design and Greenery

Because people in cold climates spend much of the year indoors, design should prioritize daylight, nature views, and indoor greenery, while shaping outdoor environments to reduce climate discomfort. Microclimatic design can extend outdoor comfort by up to six weeks (Study 6), improving seasonal usability [52]. Strategies include [46,53]:

- Adjusting site geometry to reduce wind exposure;
- Using vegetation for wind protection and seasonal shading;
- Employing water features to moderate local temperature;
- Selecting pavement materials that retain heat;
- Creating sheltered outdoor spaces;
- Strategically placing snowdrifts to block prevailing winds.

Regarding vegetation, few detailed recommendations appear beyond microclimatic contributions. Study 6 underscores indoor vegetation for cognitive performance, air quality, and well-being. Study 3 adds that deciduous trees near façades provide summer shading and winter solar access, enhancing thermal comfort and allowing occupants to experience seasonal change. Such design not only improves thermal balance but also strengthens biodiversity and indoor air quality.

4.11. Synthesis and Framework Implications

The systematic review highlights that biophilic design in Arctic and Sub-Arctic climates must address the extreme seasonal variations in daylight and temperature. All studies prioritized thermal comfort and natural light access, emphasizing the need for adaptive lighting systems, strategic window design, and material selections that support both circadian health and energy efficiency. Operable windows, intermediate buffer spaces, and dynamic building envelopes were identified as essential for improving indoor environmental quality and strengthening connections to nature. While considerations for outdoor activities, greenery, and water elements were less common, microclimatic strategies and the selective use of vegetation were noted for enhancing outdoor comfort. Overall, biophilic design in cold climates requires a holistic and context-specific approach to support human health and well-being.

The meta-synthesis of biophilic design approaches in Arctic and Sub-Arctic climates revealed a conceptual framework for sustainable, human-centered architectural design tailored to these extreme environments. Although the reviewed studies each addressed specific aspects of biophilic design, the findings collectively underscore the necessity of adopting a comprehensive and integrative perspective.

Figure 4 illustrates the conceptual framework that maps the relationships among architectural interventions, biophilic design parameters, and intended outcomes within

Arctic and Sub-Arctic contexts. It organizes these elements into three interconnected categories:

(1) Interventions;
(2) Design parameters;
(3) Outcomes.

Interventions, such as mechanical ventilation, microclimatic design, shading systems, intermediate spaces, window design, and adaptive building envelopes, are emphasized for their roles in improving thermal conditions. These are connected to parameters such as materials, air quality, and outdoor contact, which directly contribute to thermal comfort and variability. The framework also addresses photoperiod, capturing the importance of light, color, and views in regions characterized by dramatic seasonal shifts in daylight. It highlights how artificial lighting, window design, and indoor–outdoor perception together regulate circadian rhythms, a factor critical for well-being in northern regions. This aligns closely with findings from experimental studies that examined lighting strategies and color temperature effects.

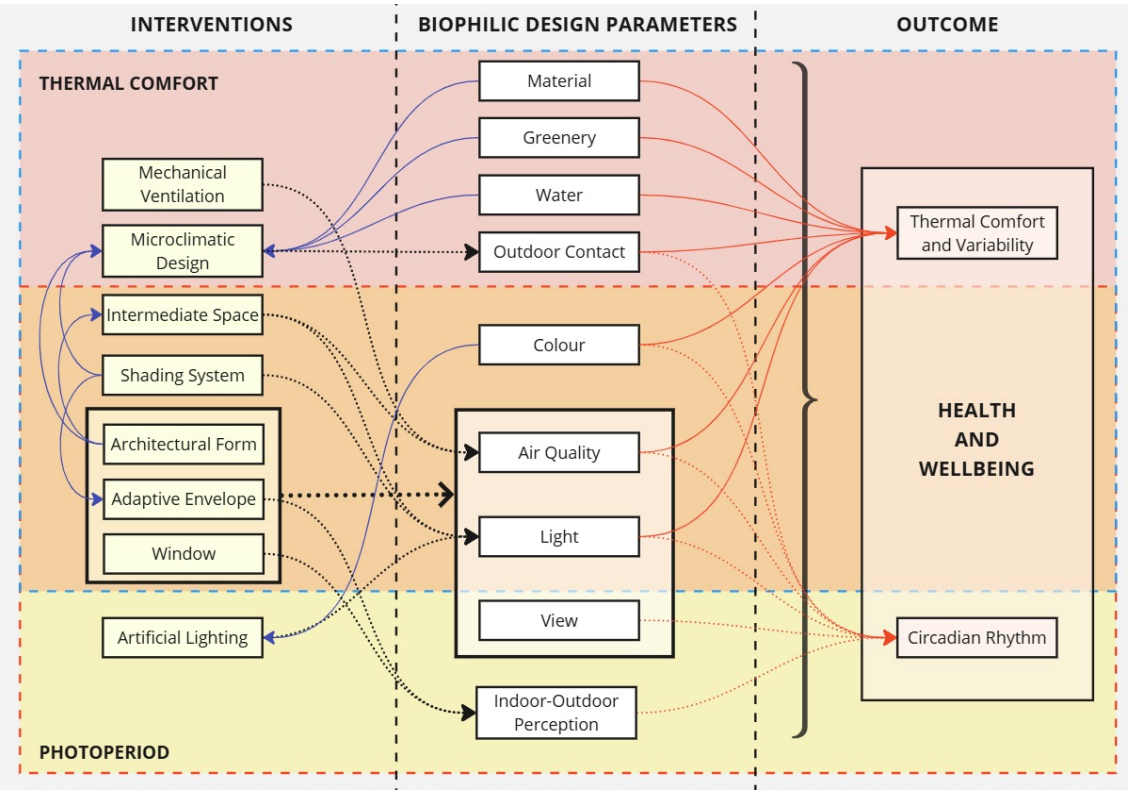


Figure 4. Conceptual framework of biophilic design in Arctic and Sub-Arctic climates.

The outcome dimension of the framework effectively links these strategies to two primary results: thermal comfort and circadian rhythm regulation, which together underpin overall health and well-being. The framework also illustrates how multiple interventions and parameters interact dynamically, reflecting the inherent complexity of biophilic design systems in cold climates.

Overall, the framework provides a clear and comprehensive visual summary of the study's findings. It reinforces the importance of climate-responsive, integrated, and human-centered design strategies for promoting health and well-being in Arctic and Sub-Arctic regions. Designers should therefore consider both the intended biophilic objectives and the complex interplay of interventions required to achieve them, particularly those supporting

thermal comfort and circadian rhythm regulation, which are vital for occupant well-being in severe climatic conditions.

4.12. Limitations and Future Research

Despite its systematic approach and methodological rigor, this study has several limitations that warrant acknowledgment. First, the scope of the dataset was inherently limited by the availability of peer-reviewed research on biophilic design in Arctic and Sub-Arctic regions. Only nine studies met the inclusion criteria, all conducted in northern Canada and primarily affiliated with the Groupe de Recherche en Ambiances Physiques (GRAP) at Université Laval. While this concentration ensured methodological consistency, it also introduced geographical and institutional bias, constraining the generalizability of the findings to other cold-climate contexts such as Scandinavia, Greenland, Russia, and Alaska.

Second, although this research followed a Systematic Literature Review (SLR) approach consistent with the SALSA and PRISMA frameworks, it focused exclusively on English-language, peer-reviewed journal articles. This may have excluded valuable studies published in other languages, particularly those from Nordic or Russian sources, and limited the global representativeness of the dataset. Future reviews could expand inclusion criteria and employ multilingual search strategies to capture a broader evidence base.

Third, while the meta-synthesis integrated both qualitative and quantitative findings, no direct comparison was made between the simulation results and national or regional building performance standards (e.g., Canadian Building Codes). Future studies should explore how design parameters such as daylight factor, glazing ratio, and thermal thresholds align with regulatory benchmarks to strengthen the evidence-based validation of biophilic strategies in cold climates.

Fourth, although the proposed "Interventions–Parameters–Outcomes" framework holistically synthesizes current knowledge, it remains theoretically grounded and would benefit from empirical validation. Future research should conduct real-world case studies in Arctic and Sub-Arctic environments to test and refine the framework by linking independent variables (e.g., materiality, spatial configuration, window design) with dependent outcomes such as user satisfaction, well-being, and building energy performance.

Finally, while this study identified thermal comfort, daylighting, and circadian regulation as the most influential variables, future investigations should further quantify the relative weight of these parameters and examine their interactions, for example, how daylighting simultaneously affects energy use, visual comfort, and psychological well-being.

By addressing these limitations, future research can advance from theoretical synthesis to evidence-based application, enhancing the global validity, cultural adaptability, and policy relevance of biophilic design in extreme cold environments.

5. Conclusions

This study presents a systematic meta-synthesis of biophilic design strategies in Arctic and Sub-Arctic climates, providing a holistic understanding of how architectural design can promote health and well-being in extreme cold environments. By synthesizing nine peer-reviewed studies, it identifies thermal comfort and daylight access as the most critical biophilic parameters, while highlighting that elements such as greenery, water, and multisensory experiences, commonly emphasized in temperate climates, are less feasible under severe environmental constraints.

The analysis reveals strong interconnections among key variables, including light, view, air quality, materiality, and thermal variability, which collectively support circadian regulation and psychological comfort. From these findings, the study proposes the

"Interventions–Parameters–Outcomes" framework as a transferable conceptual model for cold-climate design. The framework integrates adaptive envelopes, light-responsive façades, strategic window design, and intermediate buffer zones as essential interventions for supporting human physiological and psychological needs in extreme environments.

While all reviewed studies originate from northern Canada, reflecting a geographical limitation in the current body of research, this concentration also offers valuable methodological consistency. The framework developed here thus provides a context-specific but adaptable foundation, which should be empirically validated and expanded through future comparative studies across other cold regions such as Scandinavia, Greenland, and northern Russia.

Ultimately, this research contributes to the evolving field of biophilic architectural design by consolidating dispersed, parameter-specific evidence into a holistic, climate-responsive framework. It underscores the importance of localized, culturally aware, and health-centered design approaches in advancing sustainable architecture for some of the world's most challenging environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings15213825/s1, PRISMA 2020 Checklist. Reference [54] is cited in the supplementary materials.

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References

1. Kellert, S.; Calabrese, E. The Practice of Biophilic Design. 2015. Available online: www.biophilic-design.com (accessed on 23 March 2021).
2. Kellert, S.; Wilson, E.O. *The Biophilia Hypothesis*; Island Press: Washington, DC, USA, 1993.
3. Kellert, S.; Heerwagen, J.; Mador, M. *Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life*; John Wiley & Sons: Hoboken, NJ, USA, 2008.
4. Browning, W.D.; Ryan, C.O. *Nature Inside: A Biophilic Design Guide*; RIBA Publishing: London, UK, 2020.
5. Lim, P.Y.; Dillon, D.; Chew, P.K.H. A Guide to Nature Immersion: Psychological and Physiological Benefits. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5989. [CrossRef]
6. Park, S.-H.; Mattson, R.H. Ornamental Indoor Plants in Hospital Rooms Enhanced Health Outcomes of Patients Recovering from Surgery. *J. Altern. Complement. Med.* **2009**, *15*, 975–980. [CrossRef] [PubMed]
7. Ulrich, R.S. View through a window may influence recovery from surgery. *Science* **1984**, *224*, 420–421. [CrossRef] [PubMed]
8. Ulrich, R.S. Health Benefits of Gardens in Hospitals Design Guidelines View Project Healthcare Architecture View Project. In Paper for Conference, Plants for People International Exhibition Floriade 2002. Available online: https://www.researchgate.net/publication/252307449 (accessed on 31 July 2022).
9. Kweon, B.S.; Ulrich, R.S.; Walker, V.D.; Tassinary, L.G. Anger and Stress: The Role of Landscape Posters in an Office Setting. *Environ. Behav.* **2007**, *40*, 355–381. [CrossRef]
10. Silverstein, A. *A History of Immunology*; Academic Press: Cambridge, MA, USA, 2009.
11. Berman, M.G.; Jonides, J.; Kaplan, S. The Cognitive Benefits of Interacting with Nature. *Psychol. Sci.* **2008**, *19*, 1207–1212. [CrossRef]

12. Browning, W.D.; Ryan, C.O.; Clancy, J.O. *14 Patterns of Biophilic Design: Improving Health & Well-Being in the Built Environment*; Terrapin Bright Green, LLC: New York, NY, USA, 2014. Available online: https://www.terrapinbrightgreen.com/wp-content/uploads/2014/09/14-Patterns-of-Biophilic-Design-Terrapin-2014p.pdf (accessed on 19 October 2025).
13. Tekin, B.H.; Corcoran, R.; Gutiérrez, R.U. The impact of biophilic design in Maggie's Centres: A meta-synthesis analysis. *Front. Arch. Res.* **2023**, *12*, 188–207. [CrossRef]
14. Tekin, B.H.; Tunahan, G.I.; Disci, Z.N.; Ozer, H.S. Biophilic Design in the Built Environment: Trends, Gaps and Future Directions. *Buildings* **2025**, *15*, 2516. [CrossRef]
15. Tekin, B.H.; Gutiérrez, R.U. Human-centred health-care environments: A new framework for biophilic design. *Front. Med Technol.* **2023**, *5*, 1219897. [CrossRef]
16. Tekin, B.H.; Corcoran, R.; Gutiérrez, R.U. A Systematic Review and Conceptual Framework of Biophilic Design Parameters in Clinical Environments. *Health Environ. Res. Des. J.* **2023**, *16*, 233–250. [CrossRef]
17. Davy, R. *Climate of the High Arctic*; Elsevier: Amsterdam, The Netherlands, 2020; Volume 1–5. [CrossRef]
18. Serreze, M.C. *Arctic and Antarctic: Arctic Climate*; Elsevier: Amsterdam, The Netherlands, 2015. [CrossRef]
19. Serreze, M.C. *Climates of Tundra and Alpine Biomes*; Elsevier: Amsterdam, The Netherlands, 2020; Volume 2–5. [CrossRef]
20. Lotter, A.F.; Pienitz, R.; Schmidt, R. *Diatoms as Indicators of Environmental Change in Subarctic and Alpine Regions*; Cambridge University Press (CUP): Cambridge, UK, 2010; pp. 231–248.
21. Walsh, J.E.; Ballinger, T.J.; Euskirchen, E.S.; Hanna, E.; Mård, J.; Overland, J.E.; Tangen, H.; Vihma, T. Extreme weather and climate events in northern areas: A review. *Earth-Sci. Rev.* **2020**, *209*, 103324. [CrossRef]
22. Hossain, K. Climate change challenges in the arctic. In *The Palgrave Handbook of Global Sustainability*; Springer: Berlin/Heidelberg, Germany, 2023; Volume 1–3. [CrossRef]
23. Junttila, O.; Kaurin, Å. Environmental control of growth behavior and cold hardiness in arctic and subarctic plants. In *Low Temperature Stress Physiology in Crops*; CRC Press: Boca Raton, FL, USA, 2018. [CrossRef]
24. Lee, Y.K. *Arctic Plants of Svalbard: What We Learn from the Green in the Treeless White World*; Springer: Berlin/Heidelberg, Germany, 2020. [CrossRef]
25. Peterson, K.M. *Plants in Arctic Environments*; Springer: Berlin/Heidelberg, Germany, 2014. [CrossRef]
26. Grigorieva, E.A. Climate Change and Human Health in the Arctic: A Review. *Climate* **2024**, *12*, 89. [CrossRef]
27. Carleton, A.M. Antarctic climates. In *Encyclopedia of World Climatology*; Springer: Dordrecht, The Netherlands, 2005; pp. 37–54.
28. Callaghan, T.V.; Björn, L.O.; Chernov, Y.; Chapin, T.; Christensen, T.R.; Huntley, B.; Ims, R.A.; Johansson, M.; Jolly, D.; Jonasson, S.; et al. Responses to Projected Changes in Climate and UV-B at the Species Level. *AMBIO* **2004**, *33*, 418–435. [CrossRef] [PubMed]
29. Gubin, D.; Danilenko, K.; Stefani, O.; Kolomeichuk, S.; Markov, A.; Petrov, I.; Voronin, K.; Mezhakova, M.; Borisenkov, M.; Shigabaeva, A.; et al. Light Environment of Arctic Solstices is Coupled with Melatonin Phase-Amplitude Changes and Decline of Metabolic Health. *J. Pineal Res.* **2024**, *77*, e70023. [CrossRef] [PubMed]
30. Hemmersam, P. Arctic architectures. *Polar Rec.* **2016**, *52*, 412–422. [CrossRef]
31. Yardımcı, Y.; Demirel, B.B.C.; Yıldız, M.E. Climatic Influences on the Environmental Performances of Residential Buildings: A Comparative Case Study in Turkey. *Buildings* **2024**, *14*, 4015. [CrossRef]
32. Bjella, K.; Affleck, R.T.; Barna, L.; Yu, J.; Vandevort, D.; Margules, A. Arctic Expeditionary Infrastructure Research. In *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering, Proceedings of the Regional Conference on Permafrost 2021 and the 19th International Conference on Cold Regions Engineering, Online, 24–29 October 2021*; ASCE Library: Reston, VA, USA, 2021; pp. 245–252. [CrossRef]
33. Zhivotov, D.A.; Pastukh, O.A.; Panin, A.; Yablonskii, L. Application of engineering composites for elements of architectural and construction structures operated in Arctic zone. In *Proceedings of the 12th International Conference on Contemporary Problems of Architecture and Construction, ICCPAC 2020*; ICCPAC: Yerevan, Armenia, 2021; pp. 292–296.
34. Cooke, A.; Marsik, T. *Principles of Northern Housing Design with Examples from Alaska*; NREL: Washington, DC, USA, 2023. [CrossRef]
35. Vares, S.; Savolainen, P.; Häkkinen, T.; Shemeikka, J.; Huttunen, M.; Zubillaga, L. Concepts and type building for carbon neutral construction in arctic finland based on tradition. In *IOP Conference Series: Earth and Environmental Science*; IOP: Bristol, UK, 2020. [CrossRef]
36. Lapidus, A.; Khubaev, A.; Bidov, T.; Samsonov, R. Risk-oriented approach to the reconstruction of residential buildings and structures in the arctic zone. *Reliab. Theory Appl.* **2024**, *19*, 491–499. [CrossRef]
37. Mengist, W.; Soromessa, T.; Legese, G. Method for conducting systematic literature review and meta-analysis for environmental science research. *MethodsX* **2020**, *7*, 100777. [CrossRef]
38. Ouzzani, M.; Hammady, H.; Fedorowicz, Z.; Elmagarmid, A. Rayyan—A web and mobile app for systematic reviews. *Syst. Rev.* **2016**, *5*, 210. [CrossRef]
39. Baethge, C.; Goldbeck-Wood, S.; Mertens, S. SANRA—A scale for the quality assessment of narrative review articles. *Res. Integr. Peer Rev.* **2019**, *4*, 5. [CrossRef]

40. Hong, Q.N.; Fàbregues, S.; Bartlett, G.; Boardman, F.; Cargo, M.; Dagenais, P.; Gagnon, M.-P.; Griffiths, F.; Nicolau, B.; O'cAthain, A.; et al. The Mixed Methods Appraisal Tool (MMAT) version 2018 for information professionals and researchers. *Educ. Inf.* **2018**, *34*, 285–291. [CrossRef]
41. Abazari, T.; Potvin, A.; Demers, C.M.; Gosselin, L. A biophilic wellbeing framework for positive indoor-outdoor connections in energy-efficient Arctic buildings. *Build. Environ.* **2022**, *226*, 109773. [CrossRef]
42. Parsaee, M.; Demers, C.M.; Hébert, M.; Lalonde, J.-F.; Potvin, A. A photobiological approach to biophilic design in extreme climates. *Build. Environ.* **2019**, *154*, 211–226. [CrossRef]
43. Watchman, M.; Demers, C.M.H.; Potvin, A. Biophilia in school buildings: Towards a simplified assessment method based on spatial geometry. *Arch. Eng. Des. Manag.* **2021**, *18*, 434–452. [CrossRef]
44. Espinoza-Sanhueza, C.; Hébert, M.; Lalonde, J.-F.; Demers, C.M. Biophilic analogous patterns for light-responsive architecture during polar night: Examining the photobiological effects of electrical lighting on surface colour configuration. *Build. Environ.* **2023**, *249*, 111125. [CrossRef]
45. Parsaee, M.; Demers, C.M.; Potvin, A.; Lalonde, J.-F.; Inanici, M.; Hébert, M. Biophilic photobiological adaptive envelopes for sub-Arctic buildings: Exploring impacts of window sizes and shading panels' color, reflectance, and configuration. *Sol. Energy* **2021**, *220*, 802–827. [CrossRef]
46. Watchman, M.; Demers, C.M.H.; Potvin, A. Biophilic school architecture in cold climates. *Indoor Built Environ.* **2020**, *30*, 585–605. [CrossRef]
47. Abazari, T.; Potvin, A.; Gosselin, L.; Demers, C.M.H. Developing biophilic intermediate spaces for Arctic housing: Optimizing the thermal, visual, and energy performance. *Build. Simul.* **2024**, *17*, 857–875. [CrossRef]
48. Espinoza-Sanhueza, C.; Hébert, M.; Lalonde, J.-F.; Demers, C.M. Exploring light and colour patterns for remote biophilic northern architecture. *Indoor Built Environ.* **2024**, *33*, 359–376. [CrossRef]
49. Tabatabaeifard, S.A.; Lalonde, J.-F.; Hébert, M.; Potvin, A.; Demers, C.M. Exploring view access for biophilic arctic architecture through immersive visualization of integrative lighting. *J. Build. Eng.* **2023**, *69*, 106249. [CrossRef]
50. Kahraman, Ö.; Köymen, E. Examination of Winter Tourism Accommodation Building Form in Term of Compactity: The Example of Türkiye. *Sak. Univ. J. Sci.* **2023**, *27*, 1055–1078. [CrossRef]
51. Yıldız, M.E.; Beyhan, F. Prediction of cooling load via machine learning on building envelope design parameters. *J. Build. Eng.* **2025**, *100*, 111724. [CrossRef]
52. Culjat, B.; Erskine, R. Climate-responses social spaces. In *A Scandinavian Perspective, Cities Designed for Winter*; Tampere University of Technology: Tampere, Finland, 1988.
53. Li, Y.; Song, Y.; Cho, D.; Han, Z. Zonal classification of microclimates and their relationship with landscape design parameters in an urban park. *Landsc. Ecol. Eng.* **2019**, *15*, 265–276. [CrossRef]
54. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]

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