Open Access

Advances in Environmental and Engineering Research

LIDSEN Publishing Inc.

Review

Adapting Arctic Military and Cold-Region Infrastructure to Accelerating Climate Change: A 25-Year Bibliometric and Six-Nation Comparative Review

Vinayak Kaushal [1,*], Dipro Biswas [1], Amey Kashyap [2]

1. Civil Engineering Department, University of Texas at Arlington, 438 Nedderman Hall, Arlington, TX, 76010, USA; E-Mails: Vinayak.kaushal@uta.edu; dxb0219@mavs.uta.edu
2. Civil Engineering Department, University of Texas at Austin, 301E E Dean Keeton St c1700, Austin, TX, 78712, USA; E-Mail: ank2683@my.utexas.edu

* **Correspondence:** Vinayak Kaushal; E-Mail: Vinayak.kaushal@uta.edu

Academic Editor: Thomas Fickert

Special Issue: Climate Change and Environment

Adv Environ Eng Res
2026, volume 7, issue 3
doi:10.21926/aeer.2603029

Received: May 30, 2026
Accepted: August 24, 2026
Published: August 27, 2026

Abstract

Amid accelerating Arctic warming-occurring at nearly four times the global rate-cold-region infrastructure faces escalating risks from permafrost thaw, sea-level rise, and compound climate stressors. This study presents a 25-year (2001-2026) review combining bibliometric analysis with a six-nation comparative synthesis to evaluate infrastructure vulnerability, engineering adaptation strategies, and policy implementation gaps. A dataset of 1,077 Web of Science records is analyzed using VOSviewer to map thematic evolution, while detailed case comparisons across the United States, Canada, Russia, Norway, Greenland (Denmark), and China identify tested engineering practices. The findings reveal a rapidly expanding but unevenly applied knowledge base, with research concentrated on high-elevation permafrost and largely disconnected from Arctic policy and military infrastructure contexts. While multiple nations have developed coherent design philosophies-emphasizing passive cooling, ventilated foundations, geohazard-informed siting, and climate-scenario-based design-the United States remains comparatively reactive, lacking systematic adoption of these approaches. The study concludes that the primary barrier to resilience is not the absence of technical solutions but the gap between knowledge and implementation. These insights underscore the need for integrated, forward-looking design frameworks applicable not only to Arctic infrastructure but also to climate-vulnerable built environments more broadly.

Keywords

Climate-responsive design; arctic infrastructure; climate change resilience; permafrost thaw; sea-level rise; cold-region engineering; sustainable construction; environmental sustainability; military installations; bibliometric analysis

1. Introduction and Background

The Arctic and other cold regions are warming at an accelerating pace, and the infrastructure that sustains human activity across these environments is increasingly exposed to the consequences [1, 2]. The dominant stressors-thaw-induced loss of foundation bearing capacity, differential ground movement, coastal flooding and storm surge, and the accelerated deterioration of materials and structures-seldom act in isolation [1], and their combined effect is most acute where frozen ground underlies the built environment. Addressing them is an inherently interdisciplinary undertaking, drawing together geotechnical and structural engineering, building-envelope design, renewable-energy integration, and, increasingly, simulation-based analysis [3], since adequate performance in such settings depends on treating a structure and its frozen, mobile substrate as a single coupled system rather than as independent components.

Within this broader context, military installations constitute a particularly information-rich subject for review. They are comparatively well-resourced and instrumented, and they are extensively documented through defense, inspectorate, and governmental accountability reporting [4-6], allowing both the mechanisms of climate-driven deterioration and the engineered responses to them to be examined in detail [7]. The picture they present, however, is uneven. The United States has expanded its presence in the Arctic amid renewed great-power competition, yet approximately two-thirds of its installations in the region remain inadequately prepared for permafrost thaw and rising sea levels [6]. Other cold-region nations-among them Canada [3, 8] and Russia [9, 10], together with Norway [11, 12], Greenland (Denmark) [13], and China [14] examined herein-have accumulated longer and more systematic experience in frozen-ground construction, and their practices constitute a tested repertoire that the United States has yet to adopt fully.

Accordingly, the objective of this study is to provide a comparative and bibliometric review, spanning the 25-year period from 2001 to 2026, of four linked questions: the challenges that accelerating warming poses to Arctic and cold-region infrastructure, the current preparedness of U.S. military installations against those challenges, the comparative engineering responses developed by other cold-region nations, and the adaptation lessons the United States may draw from them for both existing and forthcoming installations. A bibliometric analysis of the wider literature situates this focused synthesis within a quantitative account of how the field has grown, where its contributions originate, and how its themes are organized. A consistent signal emerges throughout: conditions are changing more rapidly than adaptation is occurring [1, 2], and the evidence base is expanding accordingly-a trajectory whose implications, as the concluding section observes, ultimately extend beyond the Arctic to the built environment more broadly.

While these deficiencies are significant, they should be viewed in the context of the scale, geographic dispersion, and operational complexity of U.S. Arctic infrastructure, which present unique logistical and policy challenges. Recent initiatives, including the 2024 Department of Defense Arctic Strategy, indicate a shift toward more proactive adaptation, suggesting that institutional recognition of the problem is strengthening even as implementation remains uneven.

Infrastructure resilience, moreover, is increasingly understood as both a physical and an institutional attribute. Beyond engineering performance, resilience depends on governance structures, planning frameworks, interagency coordination, resource allocation, and adaptive decision-making capacity. The climate-adaptation challenges facing Arctic and cold-region infrastructure therefore reflect not only physical vulnerability but also institutional barriers that govern the pace of implementation-a theme to which the comparative synthesis returns repeatedly, most explicitly in the governance lessons of Section 4.1 and the recommendations of Section 6.

Contributions: This study advances the literature on climate change and cold-region infrastructure in three key ways. First, it integrates bibliometric analysis with a comparative engineering and policy review, bridging a persistent gap between the technical permafrost-engineering literature and the policy-and-installation literature on Arctic infrastructure. Second, it develops a six-nation comparative framework-spanning the United States, Canada, Russia, Norway, Greenland (Denmark), and China-to identify tested engineering practices and assess the relative positioning of U.S. military infrastructure. Third, it demonstrates that the principal constraint facing U.S. Arctic infrastructure is not the absence of engineering solutions but the lack of systematic adoption of a well-established, field-validated design repertoire. By reframing the problem as one of implementation rather than discovery, the study offers actionable insights for both infrastructure resilience and climate-adaptive engineering more broadly.

1.1 Arctic Warming

Satellite observations since 1979, taking the Arctic Circle as the region's southern limit, indicate that Arctic near-surface temperatures have risen at almost four times the global average over recent decades [15, 16]. Projections from the CMIP6 generation of climate models suggest that end-of-century Arctic warming will exceed earlier estimates-with some months warming by as much as 5°C-largely because precipitation-related processes were underrepresented in CMIP5 [17-19]. Several interacting mechanisms have been advanced to explain this phenomenon, known as Arctic Amplification (AA) [20, 21].

The mechanism most frequently invoked is the ice-albedo feedback [22, 23]: as rising temperatures shrink the sea-ice cover, the darker ocean surface that replaces it absorbs more solar radiation, reinforcing the initial warming. Across five models run under the SRES A1B scenario for the 21st century, albedo and polar temperature were found to co-vary in an essentially linear fashion [24], while the deposition of black carbon on the ice surface darkens it further and hastens melt [25]. A second driver is the intrusion of anomalously warm ocean water into the Arctic Basin [26]. Because the cold polar atmosphere responds disproportionately to incoming heat, these incursions-acting in concert with warmer winds, increasingly frequent heat waves [27], and wind-driven export of ice-have produced a year-on-year contraction of the sea-ice cover since the 1970s

[28, 29], leaving the stock of thick multiyear ice roughly 60% smaller than in the 1980s [30]. Coastal erosion is expected to intensify in step, with rates projected to grow 1.8- to 2.9-fold by the end of the century [27]-a sensitivity closely coupled to Arctic surface air temperature (SAT), which has climbed faster than the global mean relative to the historical baseline [31]. Warming also translates directly into global mean sea-level (GMSL) rise [32]: the rate accelerated from 1.1 mm/yr during 1900-1930 to 4.4 mm/yr during 2010-2015, with exposure concentrated in low-lying coastal zones [33]-and with it comes a growing flooding and erosion hazard for the infrastructure of those zones.

Permafrost degradation compounds these pressures. The same model ensembles that project rising temperatures also indicate rapid thaw [34]: active layers are deepening, and near-surface ground ice has diminished by up to 12% since 1850-and by roughly 20% in the most severely affected areas [35]. Field measurements corroborate the trend. At five monitoring sites in the western Russian Arctic, surface permafrost warmed across the board-from -8.0°C to -6.0°C at the northern sites and from -3.8°C to -1.9°C at the southern ones, converging toward -4.8°C and 0°C, respectively [36]. For cold-region infrastructure, U.S. military installations included, these trajectories are of immediate engineering consequence.

1.2 Current Base Conditions

The U.S. Department of Defense (DoD) formally acknowledged the risk to its installations in Climate Change Adaptation and Resilience (2016), a directive that distributed responsibilities among DoD components, created a dedicated climate task force, and laid out a long-term adaptation roadmap [4]. By 2019 the Department was describing climate change as a matter of national security for its bases, singling out permafrost thaw and repeated sea-level-driven flooding as the leading hazards [5]. Yet a 2022 assessment concluded that two of every three of the United States' 79 installations in the region were still exposed to climate impacts [6]. None of the six installations examined in that review had produced resilience-improvement plans, the standing directives notwithstanding: Army and Air Force leadership variously lacked familiarity with sustainability procedures, set aside the climate-risk recommendations of their own civil engineers, or made no use of the climate-projection tools available to them. Parallel interviews with Coast Guard officers and military engineers pointed to the same institutional pattern-engineers who lacked the means or mandate to act on sea-level rise and regarded it as a matter for higher authorities, a service that planned no further ahead than existing federal, state, and local guidance, and warming impacts that received attention only once infrastructure had already been damaged [7]. The 2024 DoD Arctic Strategy has since adopted a more action-oriented posture, allocating dedicated funding for permafrost mitigation at installations such as Pituffik Space Force Base in Greenland.

1.3 Objective, Scope, and Methodology

This study adopts a two-layer approach. First, a bibliometric analysis characterizes the evolution and thematic structure of the cold-region infrastructure literature between 2001 and 2026. Second, a focused comparative synthesis evaluates engineering practices across six nations to identify transferable lessons for U.S. Arctic infrastructure. Together, these approaches situate detailed engineering insights within a broader understanding of how the field has developed.

The focus on military installations is deliberate and methodological. Military infrastructure is not uniquely exposed to climate risk, but it is among the most comprehensively documented categories of cold-region infrastructure: defense agencies, inspector-general offices, governmental accountability organizations, and engineering commands publish unusually detailed, publicly available assessments of installation condition, climate vulnerability, maintenance cost, and adaptation activity-an evidence base with no equivalent for most civilian cold-region facilities. Military installations therefore serve here as a representative, information-rich lens through which the broader challenges of permafrost degradation, sea-level rise, and climate-resilient design can be examined and translated to civilian applications.

The scope is deliberately confined to the engineering of infrastructure and foundations in permafrost, Arctic, and cold-region environments under a changing climate; purely ecological, hydrological, or geophysical studies without an infrastructure dimension fall outside it. Within this scope, the review provides dedicated comparative treatment of six nations with substantial cold-region construction experience-the United States, Canada, Russia, Norway, Greenland (Denmark), and China-chosen for their documented engineering practice and their relevance as models for U.S. Arctic installations. Because the engineering challenges of frozen ground, thaw settlement, and climate-driven deterioration arise in both Arctic and high-elevation cold regions, the broader term "cold-region infrastructure" is adopted throughout this review, with "Arctic" reserved for contexts that are geographically Arctic; China accordingly enters the comparison as a high-elevation cold-region nation rather than an Arctic one.

The study employs a two-layer methodology. The first layer is a bibliometric analysis of the broader field. A topic search of the Web of Science Core Collection (SCI-EXPANDED, SSCI, and CPCI-S editions) was conducted, combining cold-region and permafrost terms with infrastructure and engineering terms and with climate-change and adaptation terms, restricted to English-language articles, reviews, and proceedings papers published between 2001 and 2026. After de-duplication and title/abstract screening against the inclusion criteria, the resulting corpus was analyzed in VOSviewer to map author-keyword co-occurrence and annual publication output characterizing the thematic organization of the field and growth. The complete search strategy-including the exact Boolean query as executed, field tags, and filters-is provided in Appendix S1 to ensure full replicability. The second layer is a focused narrative synthesis: from within the corpus, a curated subset of studies most directly addressing the four objectives and the six comparator nations was read in full and synthesized qualitatively, drawing additionally on authoritative defense, inspectorate, and governmental reports that document base conditions but are not indexed in Web of Science. Together, the two layers situate the detailed engineering review within a quantitative picture of how the field has evolved over the quarter-century.

2. Bibliometric Analysis

The Web of Science search returned 1,077 documents published between 2001 and 2026 (retrieved on 05/29/2026), from which 2,455 author keywords were extracted. After application of a thesaurus to consolidate spelling variants and synonymous terms, 50 keywords met a minimum co-occurrence threshold of nine occurrences. Their co-occurrence network, generated in VOSviewer, is presented in Figure 1 (thematic clustering) and Figure 2 (temporal overlay). A single term, permafrost (234 occurrences), dominates the network and forms its spine; the surrounding structure resolves into four principal thematic clusters. To improve interpretability, the four thematic clusters are distinguished by color in Figure 1 and identified in the caption, and Table S1 lists the mapped keywords by cluster with their occurrence counts, total link strength, and the variants consolidated by thesaurus.

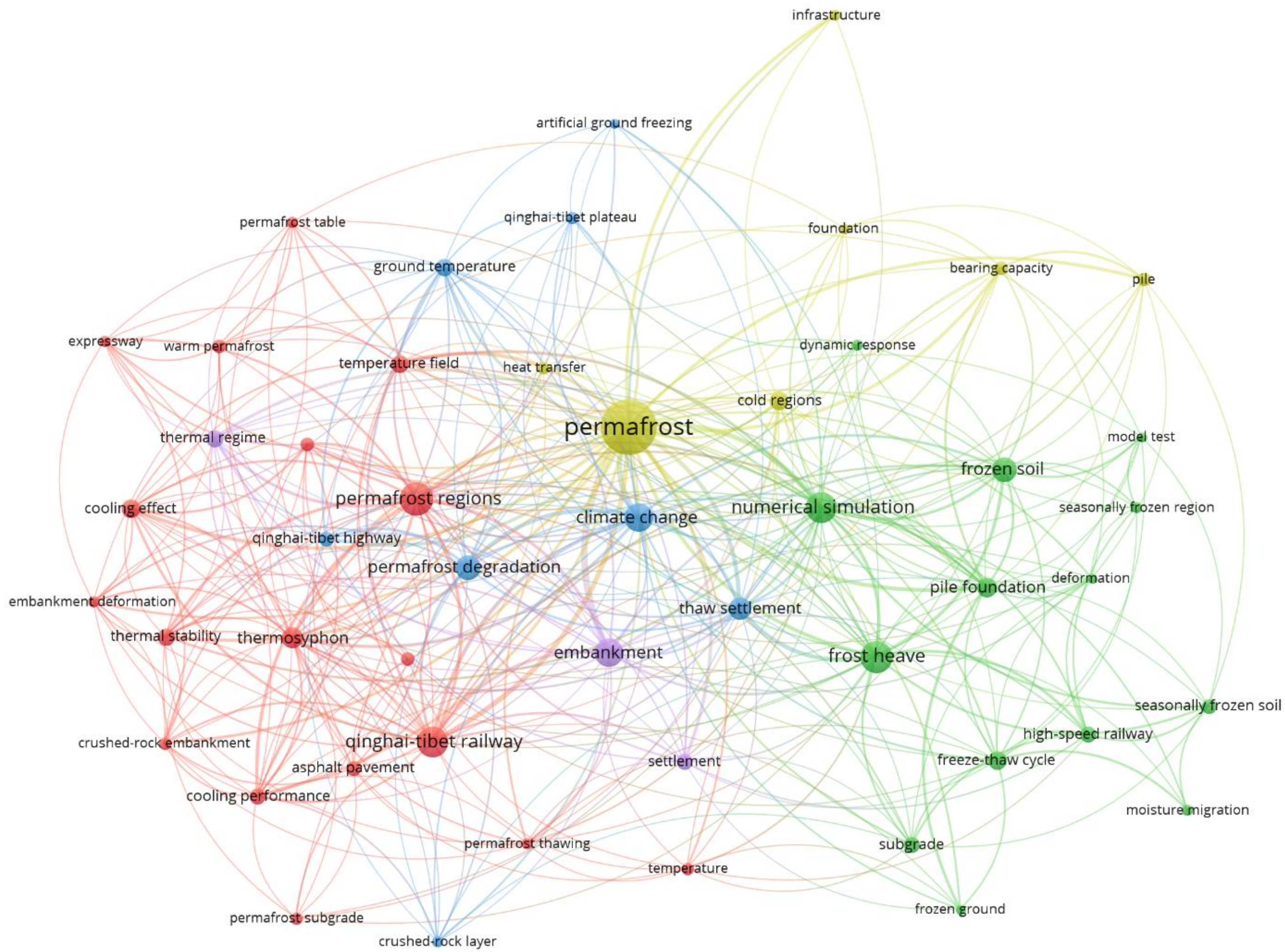

Figure 1 Co-occurrence network of author keywords. generated in VOSviewer. Node size corresponds to keyword frequency, line thickness to co-occurrence strength, and colors to the four thematic clusters discussed in the text. The figure illustrates the dominance of permafrost-centered engineering research and the near-absence of Arctic defense-focused terms-the disciplinary gap this review addresses.

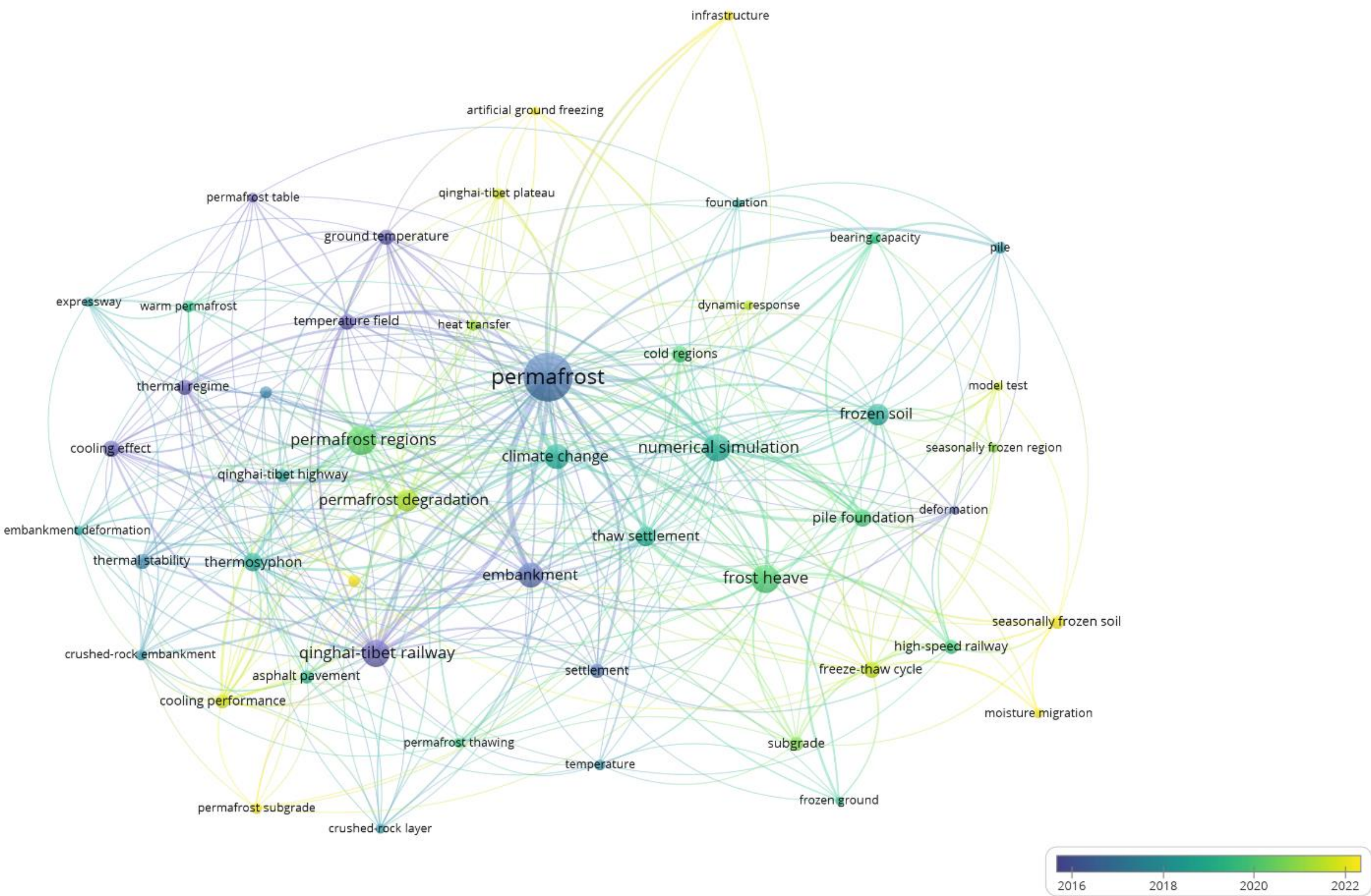

Figure 2 Temporal overlay of the keyword network with node color indicating average publication year. The visualization traces the field's evolution from passive thermal-protection themes toward predictive modeling, seasonally frozen ground processes, and climate-adaptive infrastructure design.

This network structure highlights the dominance of permafrost-centered engineering research while underscoring the limited integration of policy-relevant themes, reinforcing the need for synthesis across disciplines.

The first and largest cluster (red) concerns the passive thermal protection of transport infrastructure in warm permafrost. It links the Qinghai-Tibet railway and highway, expressways, crushed-rock embankments, asphalt pavement, and the permafrost subgrade with the techniques applied to preserve them-thermosiphons and crushed-rock layers-and with the outcomes these produce: cooling effect, cooling performance, thermal regime, and thermal stability. This is the most mature body of work in the field, addressing how embankments can keep the underlying ground frozen without active intervention.

The second cluster (green) concerns frozen-soil mechanics and foundation behavior, particularly in seasonally frozen ground. It groups frozen soil and frozen ground with frost heave, the freeze-thaw cycle, moisture migration, pile foundations, subgrade deformation, and high-speed railway applications, alongside the numerical simulation increasingly used to analyze them. Where the first cluster asks how to keep permafrost cold, this one asks how soils and foundations behave as they freeze, thaw, and heave.

The third cluster (blue) occupies the center of the map and captures the climate-process linkage: climate change, permafrost thawing, ground temperature, thaw settlement, and the embankment through which these effects are most often expressed, extending to the Qinghai-Tibet Plateau and artificial ground freezing. It acts as the conceptual bridge between the warming driver and its structural consequences.

The fourth cluster (yellow), anchored by the central permafrost hub, addresses foundations and structural loading: bearing capacity, piles, foundations, infrastructure, dynamic response, and physical model testing in cold regions-the load-bearing and structural-performance dimension of the field.

The temporal overlay (Figure 2), in which node color encodes the average year of publication, reveals a clear progression. The earliest concentrations of activity (darker shades, ≈2016-2017) lie in the Qinghai-Tibet railway, crushed-rock embankments, ground temperature, and the cooling-effect terms-the passive-protection agenda that founded the modern field. Activity matured (≈2018-2020) around permafrost degradation, climate change, numerical simulation, thaw settlement, and pile foundations. The most recent frontier (lighter shades, ≈2021-2022) shifts toward seasonally frozen ground, frost heave and moisture migration, high-speed railway, and-at the periphery-infrastructure and artificial ground freezing, signaling a broadening from continuous permafrost toward seasonally frozen regions, and from passive embankment protection toward foundation-and structure-scale concerns.

The temporal progression confirms a shift toward predictive and foundation-scale analysis, indicating that future engineering practice will increasingly depend on forward-looking and data-driven design approaches.

Two features of this landscape bear directly on the present review. First, the corpus is strongly oriented toward the high-elevation permafrost of the Qinghai-Tibet Plateau rather than the Arctic as such-a concentration that reflects the volume of Chinese cold-region engineering research and reinforces both the “cold-region” framing of this study and the inclusion of China as a comparator nation, since much of the world’s tested permafrost-engineering knowledge originates there. Second, terms denoting Arctic, military, or defense infrastructure scarcely register above the co-occurrence threshold, confirming that the engineering literature and the policy-and-installation literature on which this review also draws remain largely separate-precisely the gap this comparative synthesis seeks to bridge. The accelerating, outward-broadening trajectory evident in the overlay corroborates the study's central observation that the evidence base is expanding rapidly even as adaptation lags.

Implications of Bibliometric Patterns: Beyond descriptive mapping, the bibliometric patterns reveal structural features of the field with direct implications for practice. The rapid growth of publications since the mid-2010s reflects increasing recognition of climate-driven risks to cold-region infrastructure, yet the concentration of research within the Qinghai-Tibet Plateau context indicates a disciplinary imbalance. Arctic-specific, policy-relevant engineering studies-particularly those focused on military infrastructure-remain comparatively underrepresented. This asymmetry helps explain the lag between available engineering knowledge and its application in U.S. Arctic installations: while the technical solutions are well-developed, they are not embedded within policy frameworks or design standards in a systematic manner. The observed disconnect between clusters further reinforces the need for integrative studies that translate engineering advances into actionable infrastructure strategies.

3. Evaluating Warming Impacts on Cold-Region Infrastructure

3.1 Thawing Permafrost

Thawing permafrost undermines infrastructure through several distinct pathways. Because ice content, permafrost thickness, and ground temperature vary widely from site to site, engineering behavior in these terrains is difficult to predict [1, 2]. Ground that is frozen at the time of construction provides firm, load-resistant support; once its ice melts, that bearing capacity is lost. Thaw additionally triggers thermokarst development and retrogressive slumping-processes that reshape the soil's freeze-thaw regime [37] and can impose stresses approaching 300 kPa on the works above [1]. In the absence of established risk frameworks and the capacity for quantitative risk analysis, engineers have had to fall back on qualitative judgment, to the detriment of base performance [38]. Whole installations, moreover, stand on permafrost that is now degrading [39]: about 70% of all Arctic infrastructure rests on frozen ground, and roughly a third of that is sensitive to warming [40]. The form the permafrost takes also matters [41]. Sporadic permafrost binds soil constituents together, and its loss leaves irregular, hummocky terrain; continuous permafrost, by contrast, forms the foundation stratum beneath most Alaskan installations [42]. Some 15% of U.S. training-operations infrastructure and five DoD facilities in Alaska rest on such foundations, and as continuous permafrost degrades, the resulting subsidence endangers runways and the cold-dependent testing facilities that require subzero ground (Figure 3).

Figure 3 Cracked runways at Thule (Pituffik) AFB, Greenland, from permafrost thaw and refreezing (adapted from [6, 43]) The cracking exemplifies thaw-induced differential settlement at an operational U.S. installation and motivates the foundation and passive-cooling strategies examined in Section 4.

The damage is no longer hypothetical. In Russia, a fuel-storage tank ruptured as its foundation failed, releasing on the order of 150,000 barrels of oil toward the Arctic Ocean, and cumulative losses to transport links, industrial plants, and pipelines have reached hundreds of billions of dollars [40]. Severe thaw-driven runway flooding has been recorded at Thule (Pituffik) Air Force Base, while at Eielson AFB in Alaska an official report warned of complications for F-35A operations arising from thaw beneath the base [6], where hangars sit atop actively degrading permafrost with direct consequences for load-bearing capacity [44]. Climate considerations scarcely entered base design before the 1960s [39], and even once they did, long-term durability was rarely a design objective. In Alaskan and Canadian practice, the recurring problems are surface deformation, cracking and voids in foundations, and ponding of water along roadsides [1]. The bill for such damage may exceed $2 billion for the United States in the near term [39], rising to $7.3-14.5 billion by 2080 [45, 46]. The Alaska-Canada Highway (ALCAN) illustrates a further, self-inflicted pathway: its builders stripped away the organic cover that had insulated the underlying permafrost [47], clearing forest and tundra and thereby accelerating thaw beneath a road that now serves military logistics.

3.2 Rising Sea Levels

Arctic warming feeds sea-level rise through accelerating ice loss, and the repercussions reach coastal infrastructure, maritime facilities, training ranges, and the supply chains that connect them [42]. A U.S. Naval War College paper had sketched these implications as early as 1990, but its claims were thinly substantiated and drew little response from civil engineers and planners. Today, 128 U.S. military bases-many of them in the Arctic-stand exposed to rising seas [10], and the DoD assesses two-thirds of its Arctic bases as facing recurrent flooding (Figure 4) [6]. A base need not suffer outright physical destruction to be lost to service [48]: without connectivity, transport links, power supply, and essential materials, it cannot operate.

Figure 4 Storm damage to hangars at Eareckson Air Station, Alaska (adapted from [6, 43]). The damage illustrates how compound coastal stressors-storm surge acting on already-exposed infrastructure-translate directly into lost operational capacity.

Sea-level rise multiplies these vulnerabilities. When runways and berthing areas flood, aircraft, ships, and submarines can neither deploy nor be serviced-at high tide, sometimes not at all; budgets migrate from research and development into floodwalls and land reclamation; waterlogged grounds impede movement; and controlled training areas must be redesigned [42]. The domestic record already shows the pattern. Norfolk Naval Station in Virginia has recorded roughly 1.5 ft of sea-level rise over the past hundred years, and a comparable rise projected within the next 30-50 years would carry the base past its operational threshold [42]; higher tides there have already closed several low-lying docks, cutting capacity to a third. At Joint Base Langley-Eustis, water levels have climbed 14 inches since 1930, worsening flood frequency [5]; assessments of Naval Base Coronado likewise document impaired access, and flooding across the Hampton Roads area has at times cut off 29 military installations [49]. Arctic conditions sharpen the picture further: at Fort Greely, Alaska, an adjacent stream inundated close to five acres of the base to depths of 20 ft [6], eroding roadways throughout the installation. Recent pan-Arctic assessments sharpen this picture: roughly 60% of detected Arctic coastal infrastructure lies in low-lying zones, and a large share of coastal settlements is projected to be exposed to sea-level rise by 2100 [50], while the compound action of thaw subsidence, sea-level rise, and erosion may transform six to eight times more land than erosion alone, placing 40-65% of infrastructure in Alaskan coastal villages at risk by 2100 [51].

4. Sustainable Solutions and Discussion

The engineering responses reviewed below can be understood as a layered adaptation framework, progressing from passive thermal control strategies to structural design solutions, coastal protection measures, and predictive modeling approaches.

4.1 Comparative National Practice

4.1.1 Canada

Canadian military bases in the Arctic have absorbed substantial climate-related damage; between 2010 and 2018 the Canadian Armed Forces (CAF) responded to 23 environmental-disaster instances, rising from one in 2010 to six in 2018 [8]. The CAF has incorporated green-building principles into new projects through its Sustainable Development Strategy [52], consistent with Canada's broader Arctic strategy [49]. Canadian engineering has emphasized understanding ground ice and terrain surveying to anticipate near-surface ice and avoid sinkholes [53, 54], with maintenance-sustained methods to prevent landslides and water pooling along highway shoulders [53]; lessons from the Dempster Highway informed the Tuktoyaktuk roadway [53]. Permafrost adaptations include replacing solar-absorbing black asphalt with gravel, heat pipes that refroze the ground (90% and 60% effective at two sites), and surface insulation [55], together with foundation types-spread footing, the wood-blocking method, and jack pads-suited to permafrost [1]. More recently, a data-driven framework coupling long short-term memory networks with reanalysis and regional climate projections has been used to assess thaw threat along the Hudson Bay Railway, the Mackenzie Northern Railway, and the Inuvik-Tuktoyaktuk Highway, finding all three already exposed [47].

4.1.2 Russia

The Russian strategy follows two pathways: permafrost maintenance (the passive method) and pre-construction thawing (the active method) [9]. In Vorkuta, crawlspace foundations implemented across many one- and two-story buildings allowed the permafrost layer to rise nine years after construction [56]. Piling foundations, developed by Mikhail Kim in the late 1950s, reduced heat conduction to preserve ground ice and enabled development on both continuous and shallow permafrost [9, 10]; pile spatial orientation matters, with metal annular-section piles, hinged ground attachment, and closer spacing reducing seismic load by 25-30% [57]. Naturally acting tubular heat stabilizers-seasonally operating cooling tubes installed in horizontal (GET) and vertical (VET) configurations-are used with piles form frigid soil plates and, near Vorkuta, lowered base temperature by 4°C [58]. The active method thaws and reinforces soil before building, stabilized by ventilation cycles, but is viable mainly in coarse-grained or discontinuous permafrost [56, 59, 60]. Recent monitoring of large industrial buildings in Yakutsk demonstrates that the preserve-frozen and accommodate-thaw principles can be combined at a single site, and the updated Russian code SP 25.13330.2020 now formalizes both [61].

4.1.3 Norway

Norway's High Arctic archipelago of Svalbard-principally Longyearbyen and Ny-Ålesund-constitutes one of the most intensively studied cold-region engineering environments outside the Qinghai-Tibet Plateau. Humlum, Instanes, and Sollid documented the core problems early [11]: thaw settlement, the loss of adfreeze bonding along pilings, and accelerated creep, noting that the active layer beneath the Svalbard Airport runway reached up to twice its design thickness. The standard Norwegian response mirrors the passive principle used in Russia: buildings are raised on piles with a ventilated air gap beneath to prevent structural heat from thawing the ground. What distinguishes recent Norwegian practice is an explicitly forward-looking methodology. Instanes and Anisimov [12] demonstrated an approach in which climate-model output is fed into engineering models to compute the warmest ground temperature a structure will experience over its full service life, allowing foundations to be designed against future rather than historical conditions. The most recent work [62] refines this by separating thaw settlement from creep settlement and quantifying how warming shortens a pile's frozen length and thus its safe bearing load, while producing updated hazard maps for Longyearbyen. A cautionary lesson is governance rather than engineering: Norway has no single agency responsible for permafrost-thaw risk, dividing it among sectoral bodies-a fragmentation that parallels, and forewarns, the U.S. interagency situation. The transferable elements are service-life climate-scenario design, ventilated pile foundations, and systematic hazard mapping ahead of construction.

4.1.4 Greenland (Denmark)

Greenlandic and Danish practice is especially relevant to the United States because a major U.S. installation-Pituffik Space Force Base (formerly Thule)-sits within Greenland’s permafrost, where the U.S. has already documented thaw-driven runway cracking, and where the 2024 DoD Arctic Strategy [63] allocated roughly $7 million for permafrost mitigation. Danish engineering capacity, centered at the Technical University of Denmark, has framed the problem in terms of siting and adaptive capacity as much as foundation type. Jungsberg et al. [13] compared two northwest Greenland communities and found siting decisive: in Qeqertarsuaq, where more buildings rest on bedrock, structures fared comparatively well, whereas in Qaanaaq, where houses sit on sedimentary deposits, differential settlement has left buildings visibly skewed. The prevailing technical solution again converges on elevated pile foundations with a ventilated crawlspace for thermal separation, supplemented by bedrock siting where terrain allows, and Greenland's Geological Survey has mapped on the order of 200 thaw-sensitive slopes, 18 of them near settlements. For the United States, the lesson is that foundation engineering begins with site selection-distinguishing competent bedrock from ice-rich sediment, and mapping geohazards before committing infrastructure.

4.1.5 China

China operates the world’s largest cold-region infrastructure system across the Qinghai-Tibet (Xizang) Plateau-railway, highway, expressway, and transmission corridors built on warm, ice-rich permafrost-and, as the bibliometric analysis in Section 2 makes clear, Chinese research now dominates the global permafrost-engineering literature. This makes China the de facto proving ground for the passive-cooling toolkit examined throughout this review: crushed-rock embankments in their U-shaped, open, and closed variants, two-phase closed thermosiphons, ventilation ducts, and graded crushed-rock runway layers, all engineered to hold the embankment cooler than the surrounding air and preserve the permafrost table [64-66]. Recent work from the same community both extends and qualifies this record. Reviews by Wu and colleagues synthesize how cryosphere change is reshaping plateau engineering [14, 67] while a 2025 multi-factor assessment projects a 26.7% decline in plateau-wide permafrost engineering stability between 2015 and 2100 under a warming and wetting climate, with ice-rich central-plateau zones degrading fastest. Crucially, the recent literature also establishes that passive cooling is not permanent: aeolian-sand infiltration can erode the cooling efficiency of crushed-rock layers along the Qinghai-Tibet Railway over roughly 20-25 years. The lesson for the United States is twofold-the full passive-cooling repertoire is field-validated at scale and ready to adopt, but it should be designed as a finite-life, combinable system rather than a permanent fix, with monitoring built in from the outset [68-85].

Across these five comparator nations, two paradigms recur-preserving frozen ground or accommodating controlled thaw-alongside shared techniques such as ventilated foundations, passive cooling, geohazard-informed siting, and emerging predictive modeling. What distinguishes the United States is not a competing philosophy but the absence of one, its posture remaining largely reactive. Table 1 consolidates this comparison and makes the asymmetry plain: a tested repertoire already exists, and the gap for the United States is one of adoption rather than discovery.

Table 1 Six-nation comparative matrix of permafrost-infrastructure design philosophy and practice.

Nation	Dominant design principle	Signature techniques	Coastal/SLR response	Representative literature	Key Transferable Lesson for the United States
United States	Reactive; inconsistent adoption	Limited; ad-hoc retrofits	Revetments, floodwalls, dry floodproofing (selective)	[6, 7, 39, 40, 42, 63, 86]	Shift from reactive retrofits to standardized, forward-looking design codes
Canada	Preserve frozen ground	Heat pipes, surface insulation, spread footings, jack pads, ML thaw-threat mapping	Erosion control at coastal communities	[3, 8, 47, 53-55]	Integrate ground-ice mapping and predictive thaw-risk assessment into design stage
Russia	Both preserve and accommodate (passive + active)	Deep pile foundations, GET/VET stabilizers, ventilated crawlspaces, pre-construction thaw	Coastal/pipeline shore protection	[9, 10, 56-58, 60, 61]	Apply dual strategy: preserve permafrost where feasible, accommodate thaw where unavoidable
Norway (Svalbard)	Preserve; service-life climate design	Ventilated pile foundations, climate-scenario foundation design, hazard mapping	Coastal-bluff stability assessment	[11, 12, 62]	Adopt climate-scenario-based service-life design methodology
Greenland (Denmark)	Preserve; siting-led	Bedrock siting, elevated piles + ventilated crawlspace, geohazard mapping	Settlement-scale vulnerability mapping	[13]	Prioritize geohazard-informed siting and bedrock anchoring
China (QXP)	Preserve (passive, at scale)	Crushed-rock embankments (UCRE/CREO/CREC), TPCT, ventilation ducts, graded crushed-rock runways	Inland plateau-limited coastal exposure	[14, 64-67]	Implement passive cooling systems at scale with monitoring and lifecycle planning

4.2 Global Solutions

4.2.1 Permafrost Cooling and Solar Refrigeration

Cooling permafrost should be at the forefront of considered solutions, since passive measures such as raising infrastructure only decelerate thaw rather than prevent it [64]. One approach makes incoming solar radiation cool the soil rather than heat it [68]: photovoltaics convert solar radiation to electricity while shielding the underlying soil, and that energy powers vapor-compression refrigeration systems (VCRS) or absorption refrigeration systems (ARS) (Figure 5) [69]. VCRS offers low electricity use, economical capacity, and temperatures well below those of permafrost; ARS operates below 0°C with a simple, seismically tolerant structure. In testing, VCRS (15-day cycles) and ARS (3 days) reached -23.55°C and -1.83°C during warm seasons. A model implementation at the Baikal-Amur railroad would reduce thaw from 4.0 m to 1.51 m over five years [68], and an optimal VCRS field configuration (200 W cooling power, 12 h cooling time, 6 m spacing, 5 m evaporator depth) raised the permafrost table 1.5 m after 30 years [70].

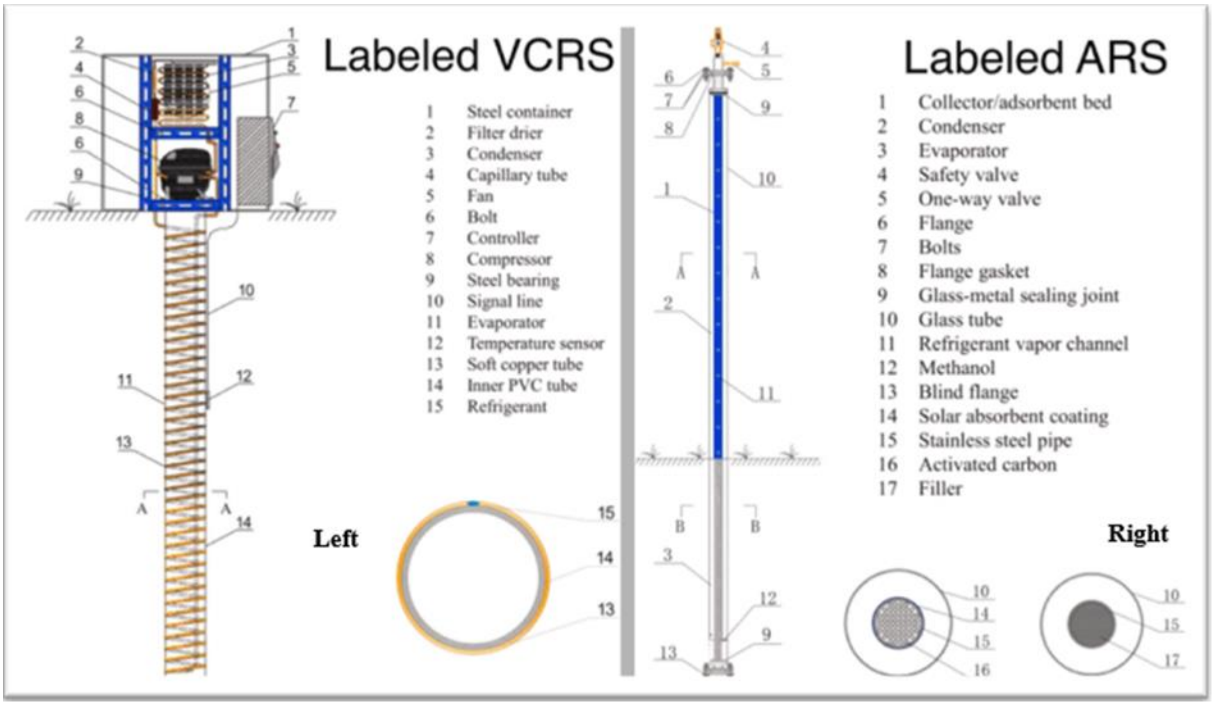

Figure 5 Vapor-compression refrigeration system (left) and absorption refrigeration system (right) (adapted from [43, 69]). For the optimized VCRS field configuration, the evaporator is installed at ≈5 m depth with ≈6 m unit spacing, at 200 W cooling power on a 12 h daily cycle [70]. The schematic shows how PV-generated electricity converts an incident solar load into active ground cooling-the only reviewed solution class that reverses, rather than merely retards, heat input to the permafrost.

From the standpoint of power-supply design, the reviewed studies indicate per-unit cooling powers on the order of 200 W under optimized VCRS configurations, operated on roughly 12-hour daily cycles, so that the electrical demand of a multi-unit field installation scales with unit count and duty cycle rather than with individually large loads. Electricity consumption otherwise varies with operating schedule, ambient climate, and refrigeration-cycle characteristics: VCRS delivers greater cooling performance per unit but depends on continuous electrical input, whereas ARS draws most of its energy as heat and therefore imposes lower electrical requirements-an important distinction for photovoltaic (PV) array sizing at remote sites. Detailed consumption values are not consistently reported across the literature, and future deployment studies should prioritize life-cycle energy performance and renewable-energy integration.

In terms of field implementation, these solar-refrigeration concepts remain at the modeled and pilot stage-principally the Baikal-Amur corridor model in Russia [68] and embankment-cooling studies in China [69, 70]-in contrast to the passive devices of Section 4.2.2, which are deployed operationally at scale across the permafrost nations examined here.

4.2.2 Thermosiphons and Thermopiles

Thermosiphons enable passive heat exchange (Figure 6), relaying heat from frozen soils to the atmosphere through the natural circulation of a working fluid [3, 62, 71]; they measure 1.8-2.0 m in radius and work best inserted into slopes at 25-30°C. A cone-penetration test found that thermosiphons cooled soil from -0.5°C to -0.8°C and increased pile-bearing capacity by 42% to 77 tons [72]. In a peat subarctic environment, simple (STS) and advanced (ATS) systems were compared [73]: although ATS minima (-13.3 to -14.2°C) were lower than STS (below 0°C), STS combined with snow-reduction cones proved a cost-effective, reliable, and versatile solution. Thermopiles combine thermosiphons and piles (Figure 7) to maintain permafrost tables under larger loads [3, 74]; in winter, fluid circulates between evaporator and condenser, while convection ceases in summer when the ground-air gradient falls below threshold [75]. A simulation using thermal coils with carbon dioxide as coolant reduced surrounding soil temperature more than standard piles and lowered thaw extent by 50% [75, 76]. Recent field studies refine these devices further-comparing straight and L-shaped two-phase closed thermosiphons over multi-year monitoring with sustainability and techno-economic assessment [77].

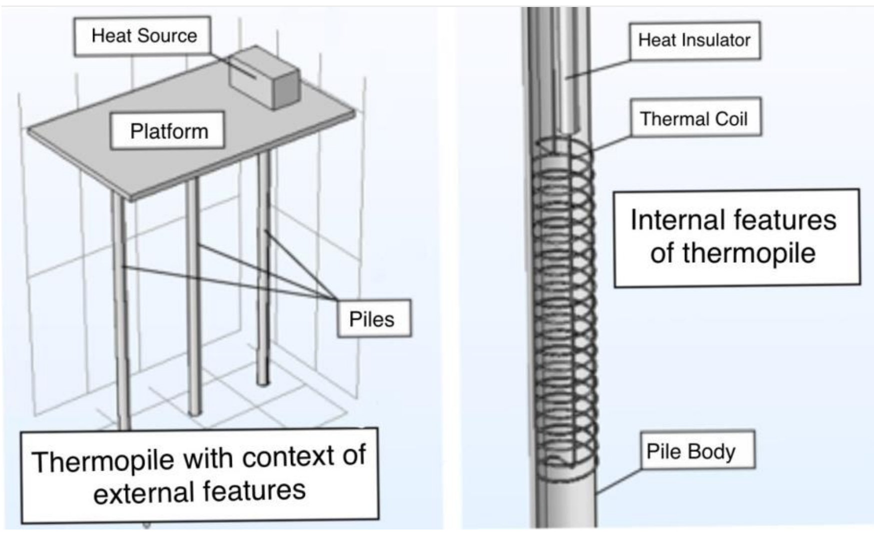

Figure 6 A labeled thermosiphon design (adapted from [43, 76]). The device's passive, zero-power operation-heat is rejected only when the air is colder than the ground-makes it the most widely field-validated cooling technology in permafrost engineering.

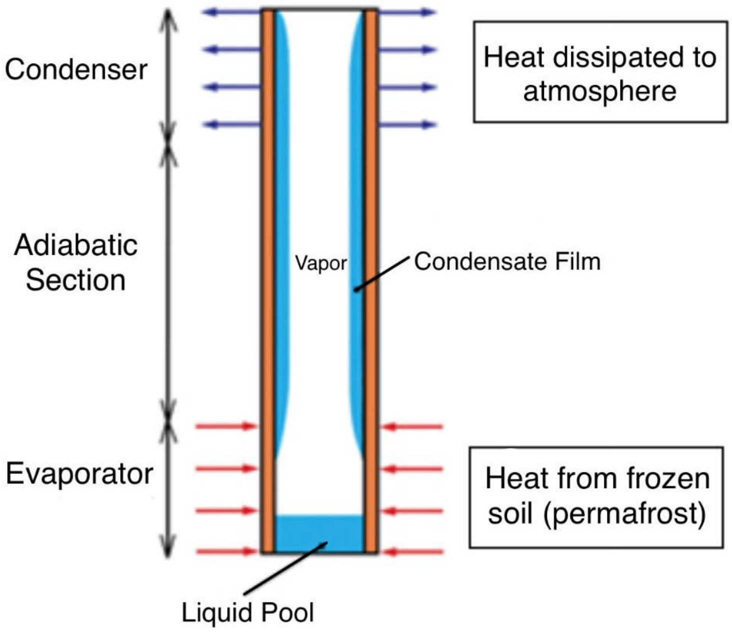

Figure 7 A labeled thermopile design (adapted from [43, 78]). By integrating the thermosiphon cycle into the load-bearing pile itself, the thermopile couples ground cooling with structural support, sustaining bearing capacity under larger loads than a standalone thermosiphon.

Unlike solar refrigeration, these passive devices have long field-deployment records across the comparator nations: thermosiphons and thermopiles protect embankments and structures along the Qinghai-Tibet corridor in China [64], support pipeline and foundation applications in Alaska and northern Canada [9, 71, 73], and appear in Russian pile practice in combination with the GET/VET stabilizers of Section 4.1.2 [58]. This breadth of operational experience is precisely what places them at the highest readiness level among the cooling technologies reviewed (Section 4.4).

Although requiring ventilation ducts to stabilize soil temperatures in warmer permafrost [79], crushed rocks use natural convection to counter thaw [64]: in winter, convection within the rocks releases heat to the atmosphere, while in summer the rocks insulate and reduce heat transfer to the permafrost. Three crushed rock-based embankments-U-type (UCRE), opened (CREO), and closed (CREC)-were analyzed in Beiluhe [65]; after two years, the lowest soil temperatures beneath UCRE and CREO were similar at -9.5°C, outperforming CREC at -4.0°C. Layered crushed rock has succeeded as runway material at small permafrost airports, including the Alaska Arctic Coastal Plain, Brookes Mountain Area, and the Mohe Gulian and Yichun airports in China [66]; an optimal crushed-rock layer (≈6-8 cm particle size, 0.5 m depth) over a 0.15-0.20 m insulation layer best sustains permafrost tables and aircraft loads.

4.2.3 Foundations

Foundation design must answer two questions: how to maintain frozen conditions to avoid critical deformation, or how to sustain structures on already-thawed terrain [10]. Alongside piling, Multipoint Foundations (Figure 8) are spatially designed, ventilated understructures of reinforced concrete, metal, or timber, with a recommended ventilation space of about 1.5 m [80]; the Abovsky spatial foundation combines a lower belt on the outer soil with an upper belt linked by a metal beam

[10], with several orientations (plate-rod, structural plate, cross-beam, folds, shells, adjustable height). These foundations require little excavation, resist permafrost-induced deformation, use factory-made components, and permit year-round construction; COMSOL analysis showed negative temperatures beneath the foundation even in the hottest month after four years [80]. Ventilation ducts cool permafrost by forced convection of residual building heat [64, 79, 81]; concrete ducts in Beiluhe ran only 1.6-1.8°C above ambient, and shutters lowered soil temperature 0.45°C at 3.5 m depth, with precast admixtures (fly ash, slag, silica fume) and insulation improving durability [81]. Material choice matters: wood (Figure 9) is lightweight, environmentally friendly, and low in thermal conductivity, reducing heat transfer to the permafrost [10], whereas reinforced concrete and metals are discouraged; modular pavements of composites or rubber granules resist underlying thaw [82].

Figure 8 Multipoint Foundation made of a steel shell (adapted from [10, 43]). The prefabricated, ventilated spatial understructure permits year-round installation with minimal excavation-attributes that make it one of the few high-capacity foundation options practical for remote cold-region sites.

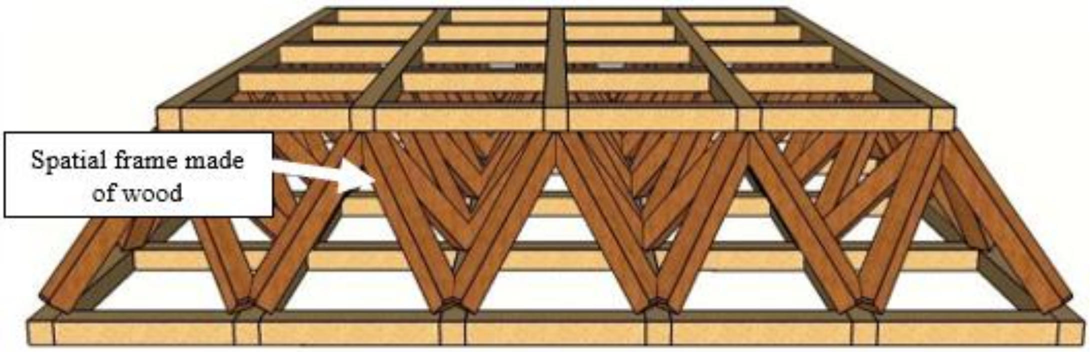

Figure 9 Structural plate foundation made of wood (adapted from [10, 43]). Timber's low thermal conductivity minimizes heat transfer into the underlying permafrost, illustrating how material selection itself functions as a thermal-protection strategy for lighter structures.

The two illustrated systems occupy complementary niches. The steel-shell Multipoint Foundation (Figure 8) offers superior structural capacity, durability, geometric adjustability, and suitability for heavier infrastructure-runways, industrial buildings, and logistics facilities-but its higher thermal conductivity requires that the ventilated gap be preserved, and its material cost and embodied carbon are greater. The wooden structural-plate foundation (Figure 9) offers markedly lower thermal conductivity (minimizing heat transfer to the permafrost), lighter installation loads, lower cost, and reduced environmental impact, but with lower load capacity and durability limitations from moisture and biological degradation that confine it to small- and medium-scale structures. Steel systems are therefore preferable for heavy infrastructure, while timber remains advantageous for lighter structures in environmentally sensitive settings. As to financial feasibility relative to conventional deep-pile retrofits, the literature documents cost-relevant advantages-minimal excavation, factory prefabrication, and year-round installation, all of which reduce mobilization and schedule costs at remote sites-but published head-to-head cost comparisons are not yet available; we identify this as a research gap.

4.2.4 Preventative Measures

Several measures can prevent existing sea-level and permafrost concerns from worsening. Revetments (Figure 10), composed of individual stone and concrete shapes placed along shorelines, are modular-accommodating rising seas and settling without restricting water flow-and a meta-analysis found them to have the fewest reported failures, applied at sites with erosion rates of 0.3-2.4 m/yr and used more than any other method (41%) [83, 84]; in the Beaufort Sea they proved most cost-effective against 2- to 500-year storms [85]. Levees offer excellent protection and can be multipurposed, but carry high upfront cost and ~2% annual maintenance [83], while bulkheads, groynes, and breakwaters are generally dissuaded [84]. Floodwalls (Figure 11), built 1-20 ft high, are cost-effective and require only periodic crack maintenance; officials at 7 of 15 Arctic bases cited raising floodwalls as a viable response to storms [86], and they can protect vessel and submarine systems from saltwater damage. Dry floodproofing makes building exteriors watertight using concrete, brick, aluminum, or fiberglass [87, 88], and Joint Base Langley-Eustis used flood-projection models and door dams to cut sandbag use by 70% [89, 90]. These accommodation strategies, unlike most foundation methods, can be retrofitted to existing installations-an advantage made more pressing by recent evidence that thaw subsidence, sea-level rise, and erosion act in compound [50, 51].

Figure 10 Rock revetments along the Alaskan Arctic coast (adapted from [43, 90]). Revetments show the fewest reported failures of any coastal-protection class and, unlike foundation strategies, can be retrofitted to existing shorelines-making them the most immediately deployable response to compound coastal hazards.

Figure 11 Floodwall along the coastline (adapted from [43, 91]). Identified by officials at 7 of 15 Arctic bases as a viable storm response, floodwalls exemplify low-maintenance accommodation measures that protect high-value waterfront assets without altering the structures themselves.

Environmental Sustainability Considerations: Climate-resilient infrastructure provides both operational and environmental benefits, and the energy balance of the reviewed cooling strategies is central to that assessment. Passive technologies-thermosiphons, crushed-rock embankments, ventilated crawlspaces, and thermopiles-require little or no external energy input: they operate on natural convection and seasonal temperature gradients, impose no continuous electrical load, and remain functional through power disruptions, an attribute of particular value to military installations pursuing energy autonomy. Active cooling by refrigeration (VCRS/ARS, Section 4.2.1) trades a continuous electrical demand for controllability and lower achievable ground temperatures; when that demand is met photovoltaically, operational emissions are limited, but array sizing, storage, and maintenance burdens grow with the cooled area. Life-cycle energy demand and greenhouse-gas emissions therefore favor passive-first, hybrid configurations in which active cooling supplements degrading passive systems rather than replacing them. Material choices carry parallel implications: timber foundations embody less carbon and conduct less heat than steel or reinforced concrete, at the price of capacity and durability (Section 4.2.3). Conversely, the environmental cost of inaction is severe. Infrastructure failure in thawing permafrost can precipitate hydrocarbon spills, sediment mobilization, debris generation, and ecosystem disturbance-the 2020 Norilsk fuel release being the starkest demonstration of the catastrophic environmental potential of foundation failure in degrading permafrost [40]. Adaptation investment should accordingly be understood not only as a resilience measure but as an environmental-protection strategy, and future assessments should embed life-cycle carbon accounting and sustainability metrics in cold-region infrastructure planning.

4.3 Predictive and Digital Methods

Although the field has historically depended on field monitoring and physical or numerical simulation-the COMSOL and SCAD analyses discussed above being representative-the bibliometric overlay in Section 2 identified a more recent methodological turn toward data-driven and scenario-coupled approaches. Two developments stand out. First, climate-scenario design, exemplified by the Norwegian practice of feeding general-circulation-model output into engineering models to size foundations against the warmest ground temperature expected over a structure's service life rather than against historical conditions [12], reframes design as forward-looking. Second, machine-learning methods are increasingly used to predict permafrost behavior under uncertainty; for example, a Canadian framework couples long short-term memory networks with reanalysis data and regional climate projections to assess thaw threat along major rail and highway corridors [47]. These methods do not replace passive engineering or physical monitoring; rather, they confront the field's central difficulty-designing fifty-year infrastructure against a moving climatic target-and constitute the most direct point of contact between cold-region engineering and the broader agenda of simulation-based optimization and predictive management in the built environment. For the United States, whose installations were largely designed against historical climate, adopting scenario-based and data-driven design represents a low-regret modernization of practice.

Published results illustrate that these approaches are already actionable. The Canadian LSTM framework, trained on reanalysis data and driven by regional climate projections, classified thaw threat along entire transportation corridors and found the Hudson Bay Railway, the Mackenzie Northern Railway, and the Inuvik-Tuktoyaktuk Highway all currently exposed [47]. In Svalbard, climate-scenario engineering models quantify how projected warming shortens a pile's frozen embedment length and reduces its safe bearing load over the design life, and show that foundations dimensioned against projected end-of-life ground temperatures carry materially lower settlement risk than those dimensioned against historical climate alone, while yielding updated hazard maps for Longyearbyen [12, 62].

Table 2 synthesizes the reviewed literature across the eight themes that structure the field, from the drivers of warming through its infrastructure impacts to the engineering, predictive, and comparative responses examined above. Alongside the bibliometric clusters of Section 2, it depicts a body of knowledge that is broad and maturing yet unevenly applied-well developed on passive cooling and foundations, thinner on Arctic-specific and predictive work-reaffirming that the principal deficit lies in translating available solutions into practice rather than in the absence of solutions.

Table 2 Thematic synthesis of the literature on Arctic and cold-region infrastructure adaptation.

Theme	Representative literature	Synthesized state of knowledge
Arctic and cold-region warming	[15-17, 22, 27, 30, 33, 35, 36, 67]	Region warming about 4× the global rate; permafrost temperatures rising and active layers deepening across the circumpolar and high-elevation cryosphere
Permafrost thaw impacts on infrastructure	[1, 2, 39, 40, 45, 46, 47, 67]	Thaw reduces bearing capacity and induces settlement, thermokarst, and frost action; ~70% of Arctic infrastructure sits on permafrost, a large share at risk
Sea-level rise and coastal impacts	[32, 33, 42, 48-51]	Rising seas threaten coastal bases, docks, and supply chains; impacts compound with erosion
Passive cooling (crushed rock, thermosiphons, ventilation)	[64-66, 68-70, 72-75, 77, 81]	Passive structures hold embankments below ambient and preserve the permafrost table; most field-validated solution class
Foundations (piles, spatial/multipoint, materials)	[3, 9, 10, 12, 56, 57, 59-61, 80]	Two design philosophies-preserve frozen ground vs. accommodate thaw; ventilated pile and spatial foundations dominate
Coastal protection and preventative measures	[50, 51, 83-88]	Revetments are the most cost-effective and lowest-failure option; floodwalls and dry floodproofing serve accommodation
Predictive and digital methods	[12, 47]	Emerging frontier: physics-informed ML and climate-scenario modeling predict thaw and bearing capacity for forward-looking design
Comparative national practice and governance	[3, 8, 9, 10, 13, 14, 52-60, 62, 63, 67]	Canada, Russia, Norway, Greenland, and China have tested repertoires the U.S. has yet to fully adopt; fragmented governance is a recurring barrier

Technology Readiness and Implementation Gaps: The U.S. adoption deficit can be stated precisely in the language the Department of Defense itself uses to manage technology maturation-the Technology Readiness Level (TRL) scale [92]. Most of the solutions reviewed here are not emerging technologies: thermosiphons and thermopiles, crushed-rock embankments, ventilated pile and spatial foundations, and coastal revetments have reached the highest readiness levels through sustained operational deployment in Canada, Russia, Norway, Greenland, and China, while PV-driven refrigeration and machine-learning-based predictive design occupy intermediate levels, validated in models and pilots but not yet standardized. The characteristic failure mode of the TRL pipeline-the “valley of death” between demonstrated technology and programmed, standardized adoption-therefore describes the U.S. position exactly: the gap lies not in research (TRL 1-4) nor in demonstration (TRL 5-7), which other nations have already supplied, but in the institutional transition to codified, funded, routine deployment (TRL 8-9). Framing the problem this way clarifies the remedy: not further invention, but the standard-setting, acquisition, and monitoring mechanisms addressed below.

Governance and Implementation Roadmap: The comparative review indicates that adaptation success depends on institutional integration as much as engineering innovation. A practical roadmap for U.S. Arctic and cold-region infrastructure would include: (1) standardized climate-scenario design requirements for new construction and major rehabilitation, on the Norwegian service-life model and the Russian SP 25.13330.2020 precedent; (2) a centralized permafrost-hazard and ground-ice database, following the Greenlandic geohazard-mapping example; (3) mandatory climate-risk assessment during infrastructure acquisition and siting; (4) expanded installation-level ground-temperature and settlement monitoring tied to the existing inspectorate reporting cycle; (5) dedicated adaptation funding streams insulated from reactive repair budgets; and (6) technology-transition pathways-pilot retrofits at the highest-risk installations such as Eielson and Pituffik, scaled through TRL-gated acquisition-linking research, demonstration, and implementation.

Economic Considerations: Although a full life-cycle cost comparison lies beyond the scope of this review, the available literature consistently indicates that proactive adaptation costs substantially less than projected climate damage. Estimated U.S. damages from permafrost thaw alone run upwards of $2 billion in the near term and $7.3-14.5 billion by 2080 (Section 3.1), whereas many of the reviewed measures can be incorporated at modest incremental cost during construction or scheduled rehabilitation: revetments proved the most cost-effective coastal defense against 2- to 500-year storm events in Beaufort Sea applications [85]; floodwalls require only periodic crack maintenance [86]; levees demand high upfront capital but predictable ~2% annual maintenance [83]; and dry floodproofing at Joint Base Langley-Eustis cut sandbag deployment by 70% with simple door dams and flood-projection models [91]. Current dedicated spending remains small against the exposure-the 2024 DoD Arctic Strategy allocates roughly $7 million for permafrost mitigation at Pituffik [63]. For the foundation and refrigeration classes (Multipoint Foundations, VCRS/ARS), published head-to-head costs against conventional retrofits are lacking, and comprehensive cost-benefit analysis across passive cooling, foundation retrofit, and coastal-protection strategies under multiple climate scenarios stands as a priority for future research.

Taken together, these strategies form a complementary system rather than isolated solutions. Effective adaptation in cold-region infrastructure depends on integrating passive cooling, foundation design, coastal protection, and predictive modeling into a unified framework responsive to both current and projected climatic conditions.

5. Limitations

This study is subject to several limitations, whose relative weight can be stated explicitly. First, the bibliometric analysis is restricted to English-language publications indexed in Web of Science; this predominantly excludes Russian- and Chinese-language journals, which host the two largest bodies of national permafrost-engineering literature, so the corpus understates the volume-though, we judge, not the technical direction-of work from those communities. Second, the comparative synthesis rests partly on governmental and institutional reports whose availability and detail vary by country; for the military dimension in particular, gray literature carries a substantial share of the evidence, and reporting standards differ across issuing organizations. Quantitatively, such gray literature-government and institutional reports, theses, and non-indexed sources-accounts for approximately 29% of the works cited here. Third-and decisively-Arctic-and military-specific engineering studies constitute a small fraction of the 1,077-record corpus (only 7.5% of records, n = 81), so that findings from the broader (predominantly Qinghai-Tibet Plateau) cold-region literature must be transferred to the Arctic military context by engineering analogy rather than direct evidence. Of the three, this scarcity of Arctic military-specific studies exerts the greatest influence on the review, because it is the constraint that cannot be offset by search breadth or additional sources. Triangulation among the bibliometric results, the peer-reviewed engineering literature, and governmental assessments mitigates-but does not eliminate-this limitation, and the direction of the resulting uncertainty is conservative: it may cause the review to understate, not overstate, Arctic-specific complications such as coastal exposure and salinity effects. Despite these constraints, the study integrates multiple independent source types to provide a robust and representative assessment of current knowledge and practice.

6. Conclusions and Recommendations

This study reviewed, over a 25-year horizon (2001-2026) and through a combined bibliometric and six-nation comparative lens, the challenges that accelerating warming poses to Arctic and cold-region infrastructure, the preparedness of U.S. military installations, the engineering responses developed by other nations, and the lessons the United States can adopt for existing and forthcoming bases. The principal conclusions and recommendations are as follows.

1. The bibliometric analysis reveals a field that has grown substantially while concentrating heavily on the high-elevation permafrost of the Qinghai-Tibet Plateau; terms denoting Arctic, military, or defense infrastructure remain marginal, indicating that the engineering literature and the policy-and-installation literature are still largely disconnected. Across both, the evidence base is expanding faster than adaptation is occurring.
2. Roughly two-thirds of U.S. military facilities in the Arctic remain susceptible to permafrost thaw and rising seas, owing to inconsistent DoD direction and the absence of sustainable engineering at the time of construction. Among the six nations examined, the United States is distinctive in lacking a settled design philosophy, responding reactively rather than by established principle.
3. The United States can draw on a tested international repertoire: Canadian heat pipes, surface insulation, and specialized footings; Russian passive and active methods, deep pile foundations, and ventilation stabilizers; Norwegian service-life climate-scenario design and

ventilated pile foundations; Danish and Greenlandic bedrock siting and geohazard mapping; and China's field-proven, large-scale passive-cooling systems.

4. Passive cooling-crushed-rock structures, thermosiphons and thermopiles, and ventilation ducts-remains the most field-validated means of preserving the permafrost table and should be heavily considered. Recent evidence, however, shows these measures have a finite service life (for example, aeolian-sand infiltration can erode crushed-rock cooling efficiency over two to three decades); they should therefore be designed as combinable, monitored systems rather than permanent fixes.
5. Foundation strategies-spatial (Abovsky) foundations, ventilation ducts, appropriate material selection, and, increasingly, climate-scenario service-life design-can eliminate many climate-related structural failures and are most effective in combination.
6. Expansion of preventative coastal measures-revetments, levees, floodwalls, and dry floodproofing-offers an effective response to rising seas and, unlike most foundation strategies, can be retrofitted to existing installations. Their urgency is heightened by recent findings that thaw subsidence, sea-level rise, and erosion act in compound, transforming far more coastline than erosion alone.
7. Predictive and digital methods-physics-informed machine learning and climate-scenario modeling-represent the field's emerging frontier and the United States' clearest opportunity to shift from historical-climate to forward-looking design.
8. Closing the implementation gap requires an integrated DoD institutional roadmap: a single office with cross-service authority for cold-region adaptation engineering standards; a unified design code embedding climate-scenario service-life design; mandatory geohazard and ground-ice mapping before siting; installation-level permafrost and settlement monitoring tied to the inspectorate reporting cycle; protected adaptation funding; and TRL-gated pilot retrofits at the highest-risk installations, scaled as performance is demonstrated.

Taken together, these findings indicate that conditions in the Arctic are changing more rapidly than the institutions responsible for its infrastructure are adapting. The convergence of thermal, foundation, and flood challenges documented here is most acute in the Arctic, but it is not confined to it: as warming progresses, temperate regions will increasingly encounter milder versions of the same coupled stressors on their built environments. The engineering knowledge accumulated at the cold extreme-and the forward-looking, scenario-based posture it now demands-therefore constitutes a resource the broader built environment would do well to monitor and from which it should begin to prepare.

Author Contributions

V.K. conceived and designed the study, developed the methodology, supervised the research, conducted formal analysis, validated findings, prepared visualizations, and led the writing of the original draft and subsequent revisions. D.B. contributed to data curation, literature collection, investigation, formal analysis, validation, visualization, and manuscript preparation and revision. A.K. contributed to data curation, investigation, resource acquisition, validation, and critical review and editing of the manuscript. All authors reviewed and approved the final manuscript.

Competing Interests

The authors have declared that no competing interests exist.

AI-Assisted Technologies Statement

Artificial intelligence (AI) tools were used solely for basic grammar correction and language refinement in the preparation of this manuscript. Specifically, OpenAI's ChatGPT was employed to improve the readability and linguistic clarity of the English text. All scientific content, data interpretation, and conclusions were developed independently by the authors. The authors have thoroughly reviewed and edited the AI-assisted text to ensure its accuracy and accept full responsibility for the content of the manuscript.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Appendix S1: Web of Science Search Strategy.
2. Table S1: 50 author keywords mapped in Figure 1 and Figure 2, by thematic cluster, with occurrence counts and total link strength.

References

1. Hjort J, Streletskiy D, Doré G, Wu Q, Bjella K, Luoto M. Impacts of permafrost degradation on infrastructure. Nat Rev Earth Environ. 2022; 3: 24-38.
2. Streletskiy DA, Clemens S, Lanckman JP, Shiklomanov NI. The costs of arctic infrastructure damages due to permafrost degradation. Environ Res Lett. 2023; 18: 015006.
3. Dourado JBDOL, Deng L, Chen Y, Chui YH. Foundations in permafrost of northern Canada: Review of geotechnical considerations in current practice and design examples. Geotechnics. 2024; 4: 285-308.
4. Resetar SA, Berg N. An initial look at DoD's activities toward climate change resiliency: An annotated bibliography [Internet]. Santa Monica, CA: RAND Corporation; 2016. Available from: https://www.rand.org/pubs/working_papers/WR1140.html#citation.
5. Office of the Under Secretary of Defense for Acquisition and Sustainment. Report on effects of a changing climate to the department of defense [Internet]. Washington, D.C.: U.S. Department of Defense; 2019. Available from: https://www.preventionweb.net/files/63171_sec335ndaareporteffectsofachangingc.pdf?startDownload=true.
6. Hadley G. IG report: USAF, army must do more to prepare arctic bases for climate change [Internet]. Arlington, VA: Air & Space Forces Magazine; 2022. Available from: https://www.airandspaceforces.com/ig-report-usaf-army-must-do-more-to-prepare-arctic-bases-for-climate-change/.
7. Lassiter J, Shealy T. An assessment of the Coast Guard's engineering operation and design decisions in preparation for sea level rise due to climate change. Proceedings of the International Conference on Sustainable Infrastructure 2017; 2017 October 26-28; New York, NY, USA. Reston, VA: American Society of Civil Engineers. pp. 38-48.

8. Barclay J, Lavoie J, MacArthur C, Nallim M. The Impacts of Climate Change on North American Defence and Security [Internet]. Peterborough, Canada: North American and Arctic Defence and Security Network; 2020. Available from: https://www.naadsn.ca/wp-content/uploads/2020/09/20_September_Climate-Change-Policy-Primer.pdf.
9. Landers K, Streletskiy D. (Un)frozen foundations: A study of permafrost construction practices in Russia, Alaska, and Canada. Ambio. 2023; 52: 1170-1183.
10. Inzhutov I, Zhadanov V, Semenov M, Amelchugov S, Klimov A, Melnikov P, et al. A comparative analysis of foundation design solutions on permafrost soils. E3S Web Conf. 2019; 110: 01019.
11. Humlum O, Instanes A, Sollid JL. Permafrost in Svalbard: A review of research history, climatic background and engineering challenges. Polar Res. 2003; 22: 191-215.
12. Instanes A. Incorporating climate warming scenarios in coastal permafrost engineering design-case studies from Svalbard and northwest Russia. Cold Reg Sci Technol. 2016; 131: 76-87.
13. Jungsberg L, Herslund LB, Nilsson K, Wang S, Tomaškovičová S, Madsen K, et al. Adaptive capacity to manage permafrost degradation in Northwest Greenland. Polar Geog. 2022; 45: 58-76.
14. Wu Q, Niu F. Permafrost changes and engineering stability in Qinghai-Xizang Plateau. Chin Sci Bull. 2013; 58: 1079-1094.
15. Rantanen M, Karpechko AY, Lipponen A, Nordling K, Hyvärinen O, Ruosteenoja K, et al. The Arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ. 2022; 3: 168.
16. You Q, Cai Z, Pepin N, Chen D, Ahrens B, Jiang Z, et al. Warming amplification over the Arctic Pole and Third Pole: Trends, mechanisms and consequences. Earth Sci Rev. 2021; 217: 103625.
17. McCrystall MR, Stroeve J, Serreze M, Forbes BC, Screen JA. New climate models reveal faster and larger increases in Arctic precipitation than previously projected. Nat Commun. 2021; 12: 6765.
18. Crawford A, Stroeve J, Smith A, Jahn A. Arctic open-water periods are projected to lengthen dramatically by 2100. Commun Earth Environ. 2021; 2: 109.
19. Shu Q, Wang Q, Årthun M, Wang S, Song Z, Zhang M, et al. Arctic Ocean amplification in a warming climate in CMIP6 models. Sci Adv. 2022; 8: eabn9755.
20. England MR, Eisenman I, Lutsko NJ, Wagner TJW. The recent emergence of arctic amplification. Geophys Res Lett. 2021; 48: e2021GL094086.
21. Chylek P, Folland C, Klett JD, Wang M, Hengartner N, Lesins G, et al. Annual mean arctic amplification 1970-2020: Observed and simulated by cMIP6 climate models. Geophysl Res Lett. 2022; 49: e2022GL099371.
22. Koenigk T, Key J, Vihma T. Climate change in the arctic. In: Physics and chemistry of the arctic atmosphere. Berlin, Germany: Springer Polar Sciences; 2020. pp. 673-705.
23. Ono J, Watanabe M, Komuro Y, Tatebe H, Abe M. Enhanced arctic warming amplification revealed in a low-emission scenario. Commun Earth Environ. 2022; 3: 27.
24. Winton M. Sea ice-albedo feedback and nonlinear arctic climate change. In: Arctic sea ice decline: Observations, projections, mechanisms, and implications. Washington, D.C.: American Geophysical Union; 2013. pp. 111-131.
25. Dobricic S, Pozzoli L. Arctic permafrost thawing. Luxembourg: Publications Office of the European Union; 2019; EUR 29940 EN. Available from: https://publications.jrc.ec.europa.eu/repository/handle/JRC109379.

26. Polyakov IV, Beszczynska A, Carmack EC, Dmitrenko IA, Fahrbach E, Frolov IE, et al. One more step toward a warmer arctic. Geophys Res Lett. 2005; 32: LI7605. doi: 10.1029/2005GL023740.
27. Nielsen DM, Pieper P, Barkhordarian A, Overduin P, Ilyina T, Brovkin V, et al. Increase in arctic coastal erosion and its sensitivity to warming in the twenty-first century. Nat Clim Change. 2022; 12: 263-270.
28. Kumar A, Yadav J, Mohan R. Global warming leading to alarming recession of the arctic sea-ice cover: Insights from remote sensing observations and model reanalysis. Heliyon. 2020; 6: e04355.
29. Esau I, Pettersson LH, Cancet M, Chapron B, Chernokulsky A, Donlon C, et al. The arctic amplification and its impact: A synthesis through satellite observations. Remote Sens. 2023; 15: 1354.
30. Overland J, Dunlea E, Box JE, Corell R, Forsius M, Kattsov V, et al. The urgency of arctic change. Polar Sci. 2019; 21: 6-13.
31. Shelef E, Griffore M, Mark S, Coleman T, Wondolowski N, Lasher GE, et al. Sensitivity of erosion-rate in permafrost landscapes to changing climatic and environmental conditions based on lake sediments from northwestern Alaska. Earths Future. 2022; 10: e2022EF002779.
32. Raj RP, Andersen OB, Johannessen JA, Gutknecht BD, Chatterjee S, Rose SK, et al. Arctic sea level budget assessment during the GRACE/Argo time period. Remote Sens. 2020; 12: 2837.
33. Sharapov D. Arctic ice changes and global warming. E3S Web Conf. 2023; 460: 08014.
34. Van Der Kolk HJ, Heijmans MM, Van Huissteden J, Pullens JW, Berendse F. Potential arctic tundra vegetation shifts in response to changing temperature, precipitation and permafrost thaw. Biogeosciences. 2016; 13: 6229-6245.
35. Langer M, Nitzbon J, Groenke B, Assmann LM, Schneider Von Deimling T, Stuenzi SM, et al. The evolution of arctic permafrost over the last 3 centuries from ensemble simulations with the CryoGridLite permafrost model. Cryosphere. 2024; 18: 363-385.
36. Vasiliev AA, Drozdov DS, Gravis AG, Malkova GV, Nyland KE, Streletskiy DA. Permafrost degradation in the western Russian arctic. Environ Res Lett. 2020; 15: 045001.
37. Jin HJ, Wu QB, Romanovsky VE. Degrading permafrost and its impacts. Adv Clim Change Res. 2021; 12: 1-5.
38. Larsen JN, Schweitzer P, Abass K, Doloisio N, Gartler S, Ingeman-Nielsen T, et al. Thawing permafrost in Arctic coastal communities: A framework for studying risks from climate change. Sustainability. 2021; 13: 2651.
39. Leddy L. Arctic Climate Change: Implications for U.S. National Security [Internet]. Washington, D.C.: American Security Project; 2020. Available from: https://www.americansecurityproject.org/wp-content/uploads/2020/09/Ref-0242-Arctic-Climate-Change.pdf.
40. Strawa AW, Latshaw G, Farkas S, Russell P, Zornetzer S. Arctic ice loss threatens national security: A path forward. Orbis. 2020; 64: 622-636.
41. Hu G, Zhao L, Wu T, Wu X, Park H, Zhu X, et al. Continued warming of the permafrost regions over the northern hemisphere under future climate change. Earths Future. 2022; 10: e2022EF002835.
42. Fuente D, Jacob N. Comprehensive analysis of climate change effects on military bases. Los Angeles, CA: University of California, Los Angeles; 2019.

43. Kaushal V, Kashyap A. Sustainable strategies to current conditions and climate change at U.S. military bases and other nations in the Arctic region: A 20-year comparative review. Climate. 2024; 12: 177.
44. Graboski AJ. The impacts of climate change and anthropogenic processes on permafrost soils and USAF infrastructure within Northern Tier Bases [Internet]. Dayton, OH: Air Force Institute of Technology; 2017. Available from: https://scholar.afit.edu/etd/814.
45. Dennison PP. Understanding and developing estimates based on practical foundation methods for Alaska's discontinuous permafrost region [Internet]. Dayton, OH: Air Force Institute of Technology; 2017. Available from: https://scholar.afit.edu/etd/1886.
46. Edlund CA. Quantifying permafrost extent, condition, and degradation at department of defense installations in the arctic [Internet]. Cambridge, MA: The SAO Astrophysics Data System; 2017. Available from: https://ui.adsabs.harvard.edu/abs/2017AGUFMNS33C..10E/abstract.
47. Fatolahzadeh Gheysari A, Maghoul P. A framework to assess permafrost thaw threat for land transportation infrastructure in northern Canada. Commun Earth Environ. 2024; 5: 167.
48. Malone LA. Human security and military preparedness. In: The law of adaptation to climate change: U.S. and international aspects. Chicago, IL: ABA Section of Environment, Energy, and Resources; 2012. pp. 847-867.
49. Hund G, Fankhauser JG, Kurzrok AJ, Sandusky JA. The intersection of national security and climate change. Richland, WA: Pacific Northwest National Laboratory; 2014.
50. Tanguy R, Bartsch A, Nitze I, Irrgang A, Petzold P, Widhalm B, et al. Pan-arctic assessment of coastal settlements and infrastructure vulnerable to coastal erosion, sea-level rise, and permafrost thaw. Earths Future. 2024; 12: e2024EF005013.
51. Creel R, Guimond J, Jones BM, Nielsen DM, Bristol E, Tweedie CE, et al. Permafrost thaw subsidence, sea-level rise, and erosion are transforming Alaska's arctic coastal zone. Proc Natl Acad Sci USA. 2024; 121: e2409411121.
52. Vlachopoulos N, Basso TL. An investigation into sustainable building evaluation strategies for use within the Canadian forces and the department of national defence. Can Mil J. 2015; 15: 36-43.
53. Hayley DW. Science to Technology – The importance of understanding the fundamentals of permafrost science for engineers practicing in the north. Proceedings of 68th Canadian Geotechnical Conference & 7th Canadian Permafrost Conference (GeoQuébec 2015); 2015 September 20-23; Quebec City, Canada. British Columbia, Canada: The Canadian Geotechnical Society. Available from: https://www.cgsconferences.ca/en/GEO2015/GEO2015_241.html.
54. Burgess MM, Oswell J, Smith SL. Government-industry collaborative monitoring of a pipeline in permafrost - the Norman Wells Pipeline experience, Canada. Proceedings of the 63rd Annual Canadian Geotechnical Conference and the 6th Canadian Permafrost Conference; 2010 September 12-16; Alberta, Canada. Richmond, BC, Canada: Canadian Geotechnical Society. pp. 579-586. Available from: https://osdp-psdo.canada.ca/dp/en/search/metadata/NRCAN-GEOSCAN-1-315319.
55. Roghangar K, Hayley J. A review of design and adaptation of embankment infrastructure built on permafrost under a changing climate. Proceedings of the 75th Canadian Geotechnical Conference, GeoCalgary; 2022 October 02-05; Alberta, Canada. Thornhill, ON: Canadian Dam Association.

56. Kotov PI, Khilimonyuk VZ. Building stability on permafrost in Vorkuta, Russia. Geogr Environ Sustain. 2021; 14: 67-74.
57. Belash TA, Mitrofanova MN. Pile foundations for areas with a joint manifestation of permafrost and high seismic activity. IOP Conf Ser Mater Sci Eng. 2018; 463: 022076.
58. Sakharov I. Modern approaches to the design of bases and foundations at permafrost zone sites with account for the effects of global warming. E3S Web Conf. 2023; 371: 02031.
59. Shur Y, Goering DJ. Climate change and foundations of buildings in permafrost regions. In: Permafrost soils. Berlin, Germany: Springer; 2009. pp. 251-260.
60. Clausen ED. Modeling the natural freezeback of piles using COMSOL Multiphysics®. Fairbanks, AK: University of Alaska Fairbanks; 2017.
61. Zhang RV, Zabolotnik SI, Zabolotnik PS. Assessment of the thermal effect of large industrial buildings on permafrost foundation soils in Yakutsk. Res Cold Arid Reg. 2023; 15: 262-267.
62. Bekele Y, Sinitsyn AO. Evaluation of foundation settlements for selected cultural heritage structures under climate change impacts. Trondheim, Norway: SINTEF; 2025. Available from: https://www.sintef.no/contentassets/b783bf9bad7346ffb0f475405cd33f34/permarich_report_09092025---signed.pdf.
63. U.S. Department of Defense. 2024 Arctic Strategy [Internet]. Washington, D.C.: U.S. Department of Defense; 2024. Available from: https://media.defense.gov/2024/Jul/22/2003507411/-1/-1/0/DOD-ARCTIC-STRATEGY-2024.PDF.
64. Ma W, Cheng G, Wu Q. Construction on permafrost foundations: Lessons learned from the Qinghai-Tibet railroad. Cold Reg Sci and Technol. 2009; 59: 3-11.
65. Wu QB, Li MY, Liu YZ. The cooling effect of crushed rock structures on permafrost under an embankment [Internet]. Available from: https://www.researchgate.net/profile/Qingbai-Wu/publication/242262665_The_cooling_effect_of_crushed_rock_structures_on_permafrost_under_an_embankment/links/53fd581e0cf22f21c2f7e3f1/The-cooling-effect-of-crushed-rock-structures-on-permafrost-under-an-embankment.pdf.
66. Liu X, Fu C, Li S. Temperature and settlement characteristics of graded crushed-rock layer for runway engineering in permafrost regions. PLoS One. 2022; 17: e0274843.
67. Xu XM, Zhang ZQ, Tai BW, Gao SR, Yang YZ, Wu QB. Climate warming and wetting poses a severe threat to permafrost engineering stability on the Qinghai-Xizang Plateau. Adv Clim Change Res. 2025; 16: 93-108.
68. Loktionov EY, Sharaborova ES, Shepitko TV. A sustainable concept for permafrost thermal stabilization. Sustain Energy Technol Assess. 2022; 52: 102003.
69. Hu T, Yue Z. Potential applications of solar refrigeration systems for permafrost cooling in embankment engineering. Case Stud Therm Eng. 2021; 26: 101086.
70. Sun Z, Liu J, Hu T, You T, Fang J. A solar compression refrigeration apparatus to cool permafrost embankment. Appl Therm Eng. 2023; 223: 120034.
71. Badache M, Aidoun Z, Eslami-Nejad P, Blessent D. Ground-coupled natural circulating devices (thermosiphons): A review of modeling, experimental and development studies. Inventions. 2019; 4: 14.
72. Volkov N, Sokolov I, Jewell R. Investigation by cone penetration tests of piled foundations in frozen soil maintained by thermosyphons. Am Sci Res J Eng Technol Sci. 2017; 31: 40-58.

73. Mastej E, Wright S, Braverman M, Devoie É, Egorov I, Quinton W. An evaluation of ground-freezing systems in a saturated subarctic peatland [Internet]. Rochester, NY: Social Science Research Network; 2022. Available from: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4297002.
74. Heilemann K. SIP-Rehabilitation of infrastructure in arctic areas: New challenges for methods, tools and materials. Oslo, Norway: SINTEF Community; 2010. Available from: https://nva.sikt.no/registration/0198cc76d591-10f081c6-9190-4b7c-9d1b-66547d9fd6d4.
75. Kudriavtcev S, Kovshun V. The investigation of load-bearing capacity of soil base for oil pipeline depending on local geocryological conditions. MATEC Web Conf. 2019; 265: 02019.
76. Lavrik A, Buslaev G, Dvoinikov M. Thermal stabilization of permafrost using thermal coils inside foundation piles. Civ Eng J. 2023; 9: 927-938.
77. Dong Y, Zhang Z, Xie C, Zhang S, Li S, Zhang A. Effect of two-phase closed thermosyphon shape on the heat transfer performance of highway embankments in permafrost regions. Appl Therm Eng. 2025; 278: 127195.
78. Mulinti R. Thermosyphons: Design theory [Internet]. Taylor, TX: Noren Products, Inc.; [cited 2026 May 29]. Available from: https://www.us-tech.com/RelId/1993046/ISvars/default/Thermosyphons_Design_Theory.htm.
79. Liu Z, Xie H, Deng B, Liu J, Chen J, Cui F. Cooling effects of interface heat control for wide permafrost subgrades. Atmosphere. 2024; 15: 299.
80. Inzhutov IS, Zhadanov VI, Nazirov RA, Servatinskii VV, Semenov MY, Amelchugov SP, et al. Research of permafrost soil thawing under the structural foundation platform. IOP Conf Ser Mater Sci Eng. 2018; 456: 012046.
81. Chen X, Wang L, Liu Z, Qin Y. A preliminary study on the long-term structural stability of ventilation ducts in cold regions. Civ Eng J. 2019; 5: 1227-1234.
82. Pospelov P, Korochkin A, Evtyukov S. Pavement design and construction in the arctic climate. Transp Res Procedia. 2021; 57: 489-494.
83. Caponigro MSB. Climate change adaptation strategies for coastal military installations: Design and planning principles for naval facilities engineering command. Seattle, WA: University of Washington; 2017.
84. Liew M, Xiao M, Jones BM, Farquharson LM, Romanovsky VE. Prevention and control measures for coastal erosion in northern high-latitude communities: A systematic review based on Alaskan case studies. Environ Res Lett. 2020; 15: 093002.
85. Scott F, Duckett F, Arenson L, Klengenberg C, Elias E. Erosion mitigation design in the arctic considering climate change impacts. Coast Eng Proc. 2023; 37: 25. doi: 10.9753/icce.v37.structures.25.
86. U.S. Government Accountability Office. Climate Change Adaptation: DOD Can Improve Infrastructure Planning and Processes to Better Account for Potential Impacts [Internet]. Washington, D.C.: U.S. Government Accountability Office; 2014. Available from: https://www.gao.gov/products/gao-14-446.
87. Marriott A. Clean, Resilient Flood Technology Options in Canada [Internet]. British Columbia, Canada: Adaptation to Climate Change Team; 2020. Available from: https://www.sfu.ca/content/sfu/act/reports/floodtechcanada/_jcr_content/main_content/download/file.res/Clean%2c%20Resilient%20Flood%20Technology%20in%20Canada.pdf.

88. Murphy E, Lyle T, Wiebe J, Hund SV, Davies M, Williamson D. Coastal flood risk assessment guidelines for building and infrastructure design: Supporting flood resilience on Canada's coasts [Internet]. Ontario, Canada: National Research Council of Canada; 2020. Available from: https://nrc-publications.canada.ca/eng/view/object/?id=b4e8e5cd-ace2-4777-866f-1bb18bff77f0.
89. Bayer S, Struck S. The Strategic Orientation of Armed Forces in Times of Climate Change [Internet]. Hamburg, Germany: German Institute for Defence and Strategic Studies; 2019. Available from: https://gids-hamburg.de/wp-content/uploads/2020/02/Research1-2019_Bayer_Struck_englisch.pdf.
90. Edwards I. USARC Releases Report on the Goals and Objectives for Arctic Research 2023-2024 [Internet]. Washington, D.C.: United States Arctic Research Commission; 2023. Available from: https://www.arcus.org/witness-the-arctic/2023/2/highlight/3.
91. Poirier L. Best Water/Environment: LPV-3.2 West Return Floodwall [Internet]. Birmingham, MI: Engineering News-Record; 2013. Available from: https://www.enr.com/articles/12906-best-waterenvironment-lpv-32-west-return-floodwall.
92. Department of Defense, Office of the Under Secretary of Defense for Research and Engineering. Technology Readiness Assessment (TRA) Guide [Internet]. Washington, D.C.: DoD; 2025. Available from: https://www.cto.mil/wp-content/uploads/2025/03/TRA-Guide-Feb2025.v2-Cleared.pdf.