Turning Crustacean Shell Waste into Arctic Solutions: Chitosan Nanotechnology to Combat Climate-Linked AMR

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Introduction

Antimicrobial Resistance (AMR) arises when microorganisms, such as bacteria, viruses, fungi, and parasites, develop the ability to survive exposure to antimicrobial drugs that were previously effective in eliminating them (Sinha, n.d.).

The World Health Organisation (WHO) has declared AMR one of the top 10 global public health threats and one of the most challenging global issues of this century. As reported by the WHO, this has contributed to 4.95 million deaths across 204 countries.

In the past two decades, various measures have been taken to address this issue; however, the progression of AMR remains unabated. Primary reasons behind this AMR are the misuse and overuse of antibiotics in various healthcare and agricultural settings (Michael, 2015). Numerous studies have shown that bacterial mutations and the spread of resistance genes via horizontal gene transfer are major contributors to AMR (Dadgostar, 2019). Infections associated with AMR lead not only to the highest morbidity and mortality rates but also to a profound threat to global health security, economic stability, and sustainable development.

Climate change is a long-term alteration and a critical challenge facing the world today, affecting the world's ecosystems, weather patterns, and human health on a global scale. Climate change is amplifying the emergence, progression, and spread of AMR by altering environmental, ecological, and microbial systems in ways that favour resistant organisms. Rising global temperatures enhance horizontal gene transfer, bacterial growth rates, and mutation frequencies which creates conditions that accelerate the evolution of resistance characteristics (FNU Nahiduzzaman, 2026).

Climate change is converting the Arctic at an extraordinary pace, with the region warming its accelerating the spread of AMR by driving extreme temperatures, and ecosystem disruptions that favour resistant pathogens. As climate-linked AMR grows, traditional approaches alone are no longer enough. We urgently need sustainable AMR technologies that minimise environmental impact, reduce selective pressure, and offer long-term resilience against emerging resistant microbes. These solutions are essential to protect both planetary health and human health in a warming world.

Chitosan, a biodegradable polymer derived from chitin found abundantly in crustacean shell waste, offers a powerful opportunity to address both environmental and AMR challenges. Crustacean shells including shrimp and crabs are currently treated as a burdensome waste

stream, yet they contain chitin that can be transformed into chitosan, a material with well-established antimicrobial properties and the ability to disrupt resistant pathogens. By converting this bio-waste into a functional, climate-aligned AMR solution, chitosan provides a sustainable pathway to reduce waste burdens while contributing to innovative strategies against the growing AMR threat. In addition, chitosan has wide applications in water purification, food industry, cosmetics, and agriculture, where it turns what was once a pollution matter into a circular economy resource. This waste valorisation will sort out the environmental burden, but it also assists in creating new job opportunities and strengthening environmentally friendly developments. This aligns well with Blue Economy and Triple Bottom Line ideas, demonstrating that ocean waste can drive sustainability and economic opportunity. This is a promising pathway in the Blue Economy where marine waste is transformed into high-value material. This offers a valuable opportunity to convert crustacean waste into a sustainable, high-value solution that supports environmental, economic, and social well-being.

The Arctic is uniquely vulnerable to climate-linked AMR due to rapid environmental change, fragile ecosystems, and limited healthcare facilities. Recent studies have suggested a link between rising temperatures due to climate change and the spread of AMR. Research in Europe this year found higher rates of resistance during warmer months (Erta Kalanxh, 2026). These factors increase the risk of resistant microbes. According to the findings, the Arctic region's warming has been speeding up at nearly four times the global average temperature (Rantanen, 2022), which causes enhanced permafrost thaw and the release of ancient microorganisms and long-dormant resistance genes into the environment. These microbial movements can be increased by newly ice-free waters and expanding shipping routes, as well as by wildlife migration and human activity, creating new pathways for resistant bacteria and genes to circulate across remote communities (Aslam & Aljasir, 2025). Extreme weather conditions and ecological stressors also increase the infection burden in humans and animals, leading to higher antimicrobial use. Climate-related changes create a cycle where environmental shifts speed up the evolution and spread of AMR, turning a health challenge into a global threat that affects the entire one health system (Heesoo Kim, 2022). The combination of climate-driven microbial shifts and increased human–environment contact positions the Arctic as a hotspot where AMR can emerge, spread, and cause disproportionate impacts on human health and security.

This article examines chitosan-based nanotechnology as a circular Blue Economy platform for mitigating climate-linked AMR risks in Arctic and coastal settings. It first outlines how Arctic warming may influence microbial mobilisation, ARG dissemination, and One Health AMR pathways before evaluating how crustacean shell waste can be transformed into chitosan nanomaterials for antimicrobial, water-treatment, and surface-protection applications. Finally, it considers feasibility, deployment boundaries, sustainability trade-offs, and future research needs.

Mechanism of Climate-Linked AMR in the Arctic

Warming in the Arctic is causing rapid permafrost thaw, and this leads to the release of biological material that has been frozen for thousands of years. Ground that remains frozen at or below 0°C (32°F) for at least two consecutive years can be identified as Permafrost. This often contains soil, rocks, and ice and is widespread in the Arctic, sub-Arctic, and high-altitude regions (Li et al., 2023). In permafrost, the upper layer is called the active layer, which thaws seasonally in summer and refreezes in winter, while these deeper layers remain frozen for millennia. Based on the percentage of the area underlying the permafrost, it can be divided into four permafrost zones: continuous (>90 %); discontinuous (50–90 %); sporadic (10–50 %); and isolated patches of permafrost (<10 %) (T. Zhang et al., 2008). As the climate warms, permafrost conditions can change drastically, releasing buried contaminants and reshaping hydrological and biogeochemical processes. Moreover, unfrozen pore water, which exists in the frozen soil, acts as a medium for ions and liquid water transfer, regulates nutrient accessibility, and enhances microbial activity even in frozen conditions. Reports find that between 2007 and 2016; the mean annual ground temperature had risen by an average of 0.29 ± 0.12 °C in the Arctic. Hence, Permafrost degradation has amplified throughout permafrost zones (Matthes et al., 2015). Once ground temperature increases and soil thaws, carbon, metal, and nutrient microorganisms trapped in frozen ground are released. Permafrost can be identified as a major reservoir of ancient, viable microorganisms, including bacteria, viruses and fungi, which have persevered for thousands to millions of years (Wu et al., 2022).

Permafrost has a heterogeneous structure, age, and organic content that support a highly diverse microbiome ranging from methanogens and methanotrophs to iron, sulphate, and ammonia-cycling bacteria. As a result of warming, permafrost thaw and previously unavailable organic materials and nutrients become accessible, enhancing microbial activity (Figure 1). Microbes also have ability to reshape thaw-released metals. Anaerobic bacteria

have potential to convert inorganic mercury into highly toxic methylmercury, while redox-related processes allow the mobilisation of these toxic metals into arctic waters (B. Zhang et al., 2024).

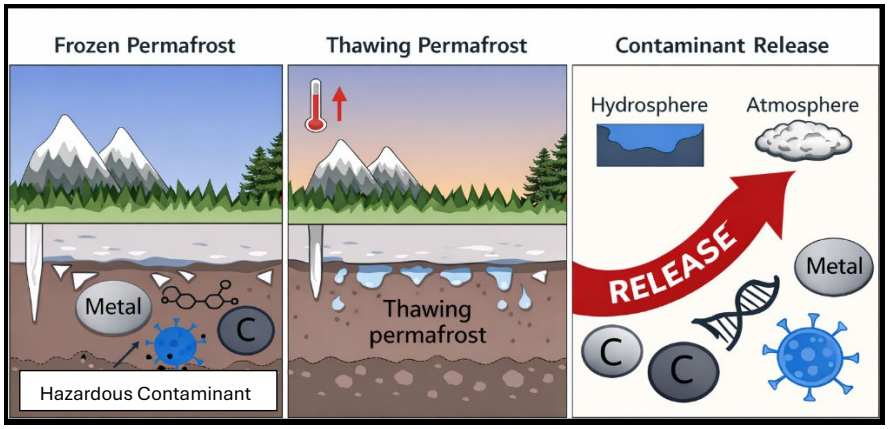

Figure 1: *Thaw-Induced Contaminant Release from Permafrost*

The polar regions (Arctic and Antarctic) are revealing an increasingly clear and concerning link between rapid environmental change and the presence, release, and spread of AMR (Depta & Niedźwiedzka-Rystwej, 2023). Climate stress increases horizontal gene transfer in the Arctic, which occurs through linked processes driven by rapid warming. First, thawing of permafrost and glaciers liberates ancient, dormant microbes and extracellular DNA (eDNA)-including diverse antibiotic resistance genes (ARGs) into active soil and water ecosystems. Second, selection and amplification, this sudden thawing triggers microbial proliferation and community restructuring that leads to new pathways for Horizontal Gene Transfer. Third, environmental stressors and other pollutants such as metals and microplastics act as co-selective agents that favour the expansion of resistant microbes and the activity of mobile genetic elements (FNU Nahiduzzaman, 2026). For instance, metagenomic and meta-omic investigations have identified that a mountain glacier contains 944 distinct Antimicrobial Resistant Genes (ARGs) spanning over 20 antibiotic classes, while comparative analysis of 43 glacier-foreland metagenomes across Arctic and Antarctic regions revealed hundreds of ARGs (Ren & Gao, 2024). Moreover, genomic mobility can be identified through large-scale profiling of the Stordalen Mire ecosystem. It has been uncovered that ~2.1 million recombinases exist across 89 microbial phyla (Guo et al., 2026). Collectively, these examples confirm that the environment is not biologically inert but serves as a dynamic source of genetic material relevant to AMR evolution.

The Arctic was identified as pristine earlier because of the minimal impact of anthropogenic activities on its environment. However, revealed that it's no longer pristine. AMR can circulate through Arctic ecosystems and throughout the world via several interconnected pathways. For instance, a recent study reported the presence of New Delhi metallo-β-lactamase-1 protein (*bla*$_{NDM-1}$) producing bacteria in the Arctic environment (McCann et al., 2019). Research stations, wastewater from settlements, mining camps, and seasonal tourism introduces human-associated microbes and antibiotic residues into fragile environments. Moreover, mitigatory birds have been identified as potential vectors for spread AMR because they're involved in spreading microbes as mechanical and biological transporters (Shu et al., 2024). In addition, marine mammals, terrestrial animals, and genes are involved in transporting resistant bacteria across large geographic ranges. Aquaculture operations further amplify AMR risks by concentrating fish stocks, increasing microbial exchange, and occasionally relying on antibiotics, creating conditions that favour the selection and spread of resistance genes (Watts et al., 2017). This is not only a serious issue for the Arctic, but it also represents a global public-health threat, as the spread of such resistance genes into wildlife and migratory bird populations and human activities enables long-distance transmission across continents and ecosystems (Figure 2).

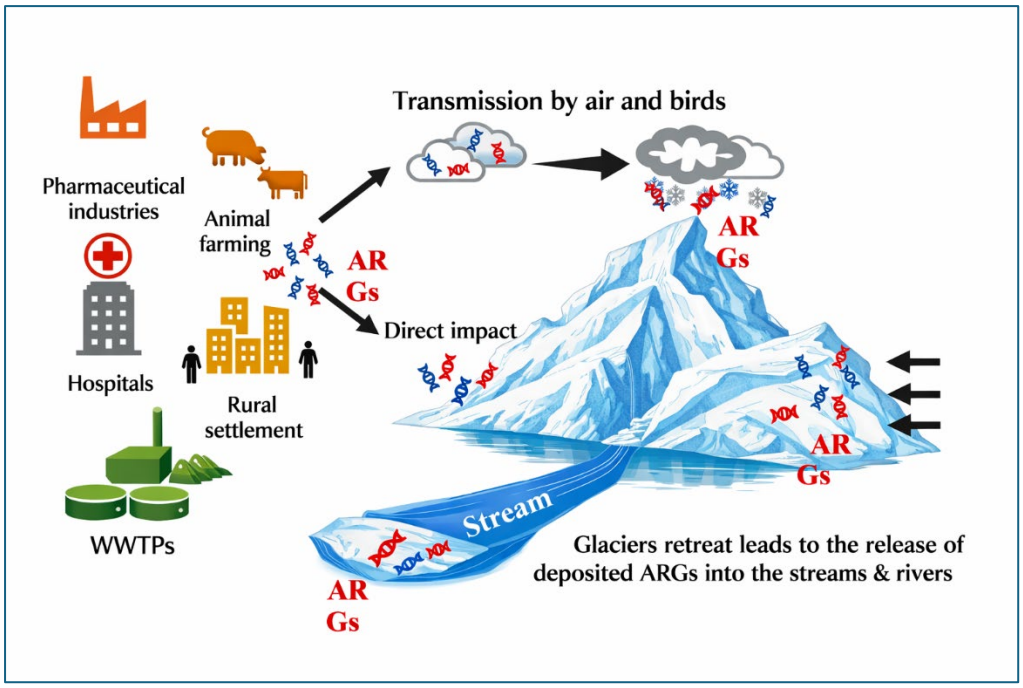

Figure 2: Pathways of Antibiotic Resistance Gene Release and Transport in Glacier-Influenced Environments

A study investigating the Arctic plasmidome in Svalbard reveals that the region is a dynamic reservoir of resistance genes and how human activity and climate change influence the spread

of ARGs and virulence genes (Makowska-Zawierucha et al., 2024). They have analysed gradients ranging from pristine glaciers to wastewater outflows and identified distinct genetic profiles associated with environmental stress and anthropogenic inputs. A study conducted at the Fairbanks Permafrost Experiment Station (Alaska) found that permafrost thaw increases AMR in soil bacteria. They found that over 91% of bacterial isolates showed resistance to Ampicillin, while the total abundance of ARGs rose with permafrost disturbance (Haan & Drown, 2021). Moreover, this study identified the isolates contained a higher proportion of plasmid-borne ARGs compared to the global soil database, suggesting that these ancient bacteria and novel genes have more potential to spread as permafrost thaws. One study that has been published by a set of scientists found that ARGs (such as aac and aph that have the ability to inactivate the antimicrobial drug called aminoglycoside) have been detected in the Mackay Glacier (Antarctica) and various glaciers in Xizang (Ying et al., 2025).

AMR in the Arctic leads unique and significant impact and threat to global health security. As warming increases, permafrost thaws, and glaciers melt, pathways open up to expose ancient ARGs and microbes. As mentioned previously, these microbes can be spread far beyond the Arctic due to migratory birds, atmospheric pathways, and human activities. This is linking remote bacterial reservoirs to global networks of infection. Ultimately, the Arctic acts as both a guard and a source of microbes, revealing how climate change, environmental disruption, and microbial evolution intersect to subvert the health balance between humans, animals, and ecosystems worldwide.

Blue Economy Framework: From Marine Waste to High-Value Biopolymer

The Blue Economy comprises the concept of sustainable use of industrial processes such as ocean, coastal, and freshwater resources for economic growth and improved livelihoods, while reducing pollution. Core principles of the Blue Economy highlight maintaining the health of the marine ecosystem, ensuring equal distribution of benefits to local communities, and stimulating innovation that reduces pollution and resource depletion around ocean-based industries (Wenhai et al., 2019). Within this framework, circular resource use has more value because it shifts the production from a linear way to regenerative systems where materials are continuously reused or transformed into high-value products. In marine contexts, this involves converting fisheries by-products into high-value products like bioactive compounds, fish leathers, etc. Not only that, marine biomass like chitin from crustaceans' shells can be converted into chitosan, which has higher economic value, thereby reducing environmental

burdens while creating new economic opportunities (Ahmed et al., 2026). The Blue Economy, by aligning ocean industries with sustainability and circularity, supports a regenerative model in which environmental stewardship, community wellbeing, and economic growth reinforce one another.

Every year, the seafood industry generates a large amount of marine biomass, which can reach around 100 million tonnes globally. This is largely composed of 6–8 million tonnes of crustacean shells, including shrimp, crab, and lobster shells. This is an opportunity to convert these chemically rich streams into industrially relevant materials such as chitin, chitosan, calcium carbonate, proteins, etc. Currently, this biomass is used for landfill disposal or is discarded directly into the environment (Vidal et al., 2022). Due to this global inadequate waste management, greenhouse gas emissions, eutrophication, and shoreline pollution have increased. In the Arctic, particularly in regions with intensive shrimp and snow crab fisheries, crustacean harvests are smaller, but the waste streams are highly concentrated. Cold temperatures slow natural decomposition; not only that, but the limited resources available in these areas also limit opportunities for valorisation, resulting in continuous waste pressure on fragile polar systems. By transforming problematic waste streams into sustainable biomaterials, such as converting chitin-rich residue into chitosan, which aligns with Blue Economy principles, it can support antimicrobial innovation for climate-linked AMR mitigation in Arctic communities while creating job opportunities.

Chitin is the second most abundant biopolymer on Earth after cellulose and is widely found in crustacean shells, squid pens, and fungal cell walls. It possesses excellent chemical properties that enhance its mechanical strength, biodegradability, and biocompatibility, making it exceptionally well-suited for applications not only in nanotechnology but also in other industries, including cosmetics, biomedical engineering, and the food sector (Barikani et al., 2014). The extraction process of chitin from marine biomass involves several steps, including demineralisation and deproteinization, which remove calcium carbonate and eliminate residual proteins from the biomass. Through deacetylation, chitin is converted into chitosan, a more water-soluble biopolymer with enhanced properties (Figure 3). Both biopolymers exhibit excellent biocompatibility, biodegradability, and antimicrobial capacity, making them ideal for biomedical, agricultural, and environmental applications. From a sustainability perspective, this process also reduces landfill burden and greenhouse gas emissions. This circular approach not only mitigates marine pollution but also fosters green innovation and local employment in coastal and Arctic regions.

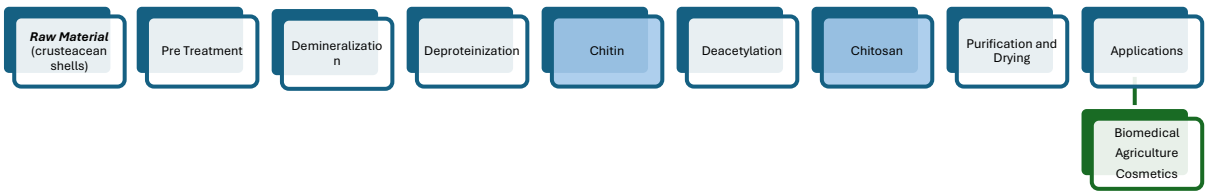

Figure 3: Extraction and valorisation of Chitin and Chitosan from Crustacean Biomass for Sustainable Industrial Applications

Chitosan production and its advancement into nanotechnology-based antimicrobial platforms represent a powerful model of sustainable innovation that closely aligns with Triple Bottom Line principles. In the environmental aspect, converting marine biomass into chitosan and further processing it as chitosan-based nanomaterial reduces the environmental burden. Not only does it have the potential to reduce the AMR burden on health care, but it also supports circular resource use. Socially, these processes create opportunities for coastal and Arctic communities through waste collection, bioprocessing, and skill development in emerging bio-nanotechnology sectors. Economically, this chitosan and chitosan-based nanotechnology open new markets in biomedical, agricultural, and environmental applications. By integrating chitosan valorisation with nanotechnology for AMR mitigation, this approach strengthens local livelihoods, green innovation, and contributes to global health resilience.

Chitosan Nanotechnology as an AMR Mitigation Tool

The structure of chitosan makes it a highly suitable material for many biological applications because its chemical composition consists of β-(1→4)-linked N-acetyl-D-glucosamine and D-glucosamine units, which provide reactive functional groups that contribute to its physicochemical versatility. It is well known for its biocompatibility, biodegradability, and safety, making it a potential renewable material for green-technology applications. Chitosan possesses intrinsic hydrophilicity, high adsorption capacity, and film-forming ability, and these properties have enabled its wide application in fields such as air and water treatment, energy systems, and biomedicine (Lv et al., 2023).

Chitosan possesses excellent antimicrobial activity through a combination of physicochemical mechanisms that directly align with AMR control. Its antimicrobial capacity, biocompatibility, and nontoxicity make chitosan an ideal material in the medical field (Dhlamini et al., 2024). The antimicrobial properties of chitosan are mainly governed by the amino groups it contains; these amino groups carry a positive charge, enhancing

electrostatic interactions between chitosan and negatively charged components on the bacterial cell membrane, thereby conferring strong antimicrobial effects. In addition, chitosan shows promising activity against bacterial DNA, as it can penetrate the cell and bind to DNA, subsequently inhibiting the synthesis of messenger RNA and proteins. Chitosan also acts as a chelating agent, binding essential metal ions such as Mg^{2+} and Ca^{2+}, as well as transition and heavy metals, forming complexes that deprive microorganisms of vital nutrients. Furthermore, its mucoadhesive properties make it a suitable candidate for drug delivery across various epithelial tissues. These multi-mechanistic actions make chitosan-based nanomaterials highly promising materials for mitigating AMR (Basit et al., 2026). Chitosan-based biomaterials also show promising activity in wound healing because they accelerate tissue repair by promoting collagen deposition and supporting faster wound closure, in addition to their antimicrobial capacity. Chitosan serves as an effective carrier for various therapeutic agents in drug-delivery systems, including chitosan-based micelles, hydrogels, porous microspheres, and composite hydrogels. It also contributes to disease diagnostics; for example, chitin-binding proteins and gold nanoparticles can distinguish between bacterial and fungal infections, and chitosan-based biosensors are used in medical testing. The United States Food and Drug Administration has approved a variety of antimicrobial dressings and drug-delivery vehicles synthesised using chitosan (Yan et al., 2021).

Nanotechnology involves the study and synthesis of materials in the size range of 1–100 nm, known as nanoparticles, which offer advantageous properties that position them as excellent candidates to complement or enhance conventional antibiotics. In nanoparticle synthesis, chitosan is used as a reducing and capping agent for metal nanoparticles, increasing surface charge density, improving cellular uptake, and enabling sustained release of antimicrobial agents. When engineered with metals such as silver, chitosan nanoparticles further enhance their ability to disrupt bacterial membranes, chelate metal ions, generate reactive oxygen species, and alter protein synthesis. As these mechanisms operate simultaneously, they reduce the likelihood of resistance development and improve efficacy against major drivers of AMR, including multidrug-resistant pathogens and biofilms (B. A et al., 2026). At the same time, chitosan nanomaterials support wider environmental and agricultural sustainability: they can purify water by binding pollutants, enhance plant growth through nano-fertilizers and protective coatings, and strengthen food safety via biodegradable antimicrobial packaging. This makes chitosan-based nanotechnology a powerful circular-economy solution,

transforming waste into high-value nanomaterials that fight AMR while improving environmental health and resource efficiency across multiple sectors.

Conceptual Arctic Deployment Model

From crustaceans' waste to chitosan framework, priority deployment sites are identified by locating Arctic environments where crustaceans waste accumulates. These include fisheries processing hubs, port reception facilities, community dumpsites, and onboard storage on fishing vessels. These are the valuable biomass streams that can be converted into chitosan, turning disposal challenges into sustainable resource pathways. During this method shell waste is first deprotonated and demineralised to obtain chitin, followed by deacetylated to produce chitosan. This process converts waste materials into a functional antimicrobial biopolymer. Hence, this deployment model begins with crustacean waste valorisation where Arctic communities can reduce waste accumulation while creating a sustainable chitin-chitosan pathway that can then support the development of diverse antimicrobial materials.

From an AMR perspective, the sites most prone to AMR contamination can be identified by tracing where meltwater channels emerging from permafrost thawing, wastewater discharge, and environmental change intersect to create conditions that favour resistant microbes. These sites are environmental points where microbial loads persist making them suitable locations for introducing chitosan-based materials. This ensures that the waste-derived chitosan pathway is applied where it can realistically reduce environmental pressures.

Chitosan as environmentally sustainable material can be converted into nanoparticles to enhance surface area stability. These nanoparticles can be function as therapeutic agents as well as act as environmental antimicrobial interfaces that bind, destabilise, or reduce microbial persistence in targeted Arctic sites. Chitosan capped silver nanoparticles have most promising activity against resistant strains as a therapeutic agent (Khalid et al., 2026).

Chitosan and chitosan-based nanomaterials behave as environmentally safe materials. Even though both materials are biodegradable, monitoring should be done when breaking them down into non-toxic sugars to ensure these materials are not accumulated in sediments or food webs. Monitoring includes seasonal sampling, autonomous sensors and community based that can track nanoparticle dispersion, degradation, and microbial shifts. Because the deployment model is grounded in waste-derived biomaterials, its ecological footprint is inherently low, but adaptive monitoring ensures responsible use and alignment with Arctic environmental priorities.

Feasibility and Boundary Conditions

The global market of chitosan shows constant supply chains and predictable pricing allowing realistic estimates of cost and their long-term availability. According to the current measures production is highest in Asia particularly China, India, and Vietnam due to the waste generation from the crustaceans-based industries (Food & Beverages, 2026). Global leaders Primex (Iceland) and Advanced Biopolymers, Novamatrix (Norway) provides direct evidence of chitosan production within Arctic region, using marine resources in the Arctic (chemicalresearch, 2026). These companies demonstrate that Arctic waste valorisation is not only feasible but already practiced at commercial scales that supports the scientific and logistical viability of chitosan production pathways. This established industrial base ensures consistent global supply, with market analyses showing steady year-on-year growth driven by biomedical, agricultural, water-treatment, and environmental applications. Waste valorisation can be positioned as a supplementary, region-focused pathway rather than a global competitor. Within this context, converting locally generated waste into chitosan creates a meaningful circular economy stream. Local sourcing allows the creation of new job opportunities, reduces transport-related emission, and aligns with Blue Economy principles offering a sustainable alternative for environmental applications.

The scalability of chitosan needs to be determined by estimating the volume of chitosan required to support environmental AMR mitigation across selected Arctic sites and determining whether regional crustacean waste streams can realistically meet the demand without creating new logistical burdens. Arctic and sub-Arctic fisheries generate substantial shell waste often exceeding 20-40% of total landed biomass and this can be identified as available biomass as a proxy for production capacity. Extraction yields of chitin lies 15-25% and chitin to chitosan conversion is around 60-80%. For instance, a single mid-sized processing facility producing ~5,000 tonnes of crustacean waste annually could generate 450–800 tonnes of chitosan, enough for large-area environmental applications when formulated as nanoparticles or coatings.

The scalability analysis indicates regional waste streams are capable to mitigate AMR in small to medium scale, especially production distribution among Arctic countries. For large scale, production deployment models would need to coordinate waste collection, seasonal processing, and potentially supplementary imports from established global procedures.

Overall, the material requirements for conceptual Arctic AMR mitigation fall within a feasible range relative to available biomass.

Arctic deployment cost feasibility depends on capable institutions that can support production, distribution, and monitoring of starting from waste valorisation to nanoparticle production. This deployment model is to mitigate AMR as an environmental public benefit rather than a commercial commodity. Furthermore, this emphasises public and scientific evaluation other than market-driven mechanisms. In real-world implementation, capital investment is typically received by local and regional governments, Arctic research institutes and universities, and environmental protection agencies all of whom are responsible for protecting the environment and supporting cross-border efforts to reduce AMR**.**

From chitosan valorisation to introducing chitosan-based material into Arctic communities and environments requires navigating several logistical constraints that shape both feasibility and scale. These key limitations include limited infrastructure, seasonal accessibility, transport challenges, and environmental permitting. These constraints collectively shape the scale, timing, and practicality of deployment. They favour modular, low-volume, high-impact applications rather than continuous large-scale dispersal. The model therefore emphasises targeted interventions at high-risk sites, seasonal deployment strategies, and integration with existing community infrastructure.

In the Arctic context, the economic case for AMR mitigation rests on recognising that the impacts of resistance already generate costs within regional systems. Because these costs are diffused and absorbed across environmental management, public services, and community wellbeing, mitigation behaves more like an infrastructure investment than a commercial product. Profit is therefore the most constrained element of the feasibility model and realistic viability depends on aligning intervention costs with the institutions and governance structures that currently manage environmental and public-health risks.

This study can be positioned as a scientific exploration of chitosan valorisation and chitosan nanoparticle-based approaches for mitigating climate-linked AMR in Arctic environments. The work evaluates feasibility, material availability, environmental fit, and deployment logic. The focus remains on understanding whether a waste-derived biopolymer can support Arctic environmental protection goals, how it behaves under relevant conditions, and what institutional structures would be required for safe and effective use. These elements help define boundary conditions for future applied research, pilot studies, or policy-supported

deployments. By keeping the scope within scientific inquiry, the study provides a foundation that future interdisciplinary teams of environmental scientists, Arctic governance bodies, and innovation funders can build upon if real-world implementation becomes desirable.

Triple Bottom Line Impact Assessment

The intervention supports Arctic region wellbeing and economy by creating new job opportunities for local community. Moreover, this deployment model has potential to support the climate-linked AMR burden in the Arctic. This approach aligns with Blue Economy principles that prioritise community health, sustainable livelihoods, and long-term resilience by converting fisheries waste into proactive biomaterials. Reduced AMR circulation, cleaner water systems, and safer food chains directly benefits the world population as it is strengthening health security without introducing new chemical burden. Beyond health protection, this approach supports skill development, empowers communities, strengthens local businesses, expands educational pathways, and enhances social resilience.

Improper disposal of this high-volume crustacean shell waste materials creates environmental liabilities related to organic pollution and landfill utilisation. This systematic reuse of waste directly advances the Blue Economy goal of turning marine by-products into high-value, environmentally safe resources. Furthermore, this reduces waste disposal pressures, prevents organic pollution, and supports healthier Arctic ecosystems. Chitosan's biodegradability ensures minimal ecological disruption, while its targeted use helps protect sensitive Arctic environments from AMR contamination. The approach demonstrates how circular resource use can enhance ecological stability in fragile Arctic systems.

Waste valorisation into functional biomaterials creates new economic value for discarded biomass which is a strong example of the Blue Economy strategy of sustainable, ocean linked innovation. Fishing industry and processing facilities gain new revenue streams and communities benefit through sustainable waste valorisation methods via circular economy resources. This waste to value pathway strengthens local economies while protecting the environment and encouraging the innovation. In this way, this deployment model can coexist with economic development in Arctic.

Ethical implementation must respect Indigenous rights, community consent, and fair distribution of benefits—core values within Blue Economy governance. Decision-making should remain transparent, culturally sensitive, and grounded in environmental justice. Regulatory oversight is needed to ensure that waste-derived innovations do not create new

inequalities or impose external priorities on Arctic communities. Responsible stewardship and inclusive governance are essential for maintaining trust and ensuring long-term legitimacy.

Research Gaps and Future Directions

In the future this model must address scientific, logistical, and governance gaps before waste-derived chitosan and chitosan-nanoparticle approaches are responsibly deployed in Arctic environments. Under the scientific category, reported data has been proven that nanoparticles have potential against AMR but available data about nanoparticle behaviour under Arctic extreme weather is limited. The extreme weather conditions such as extreme cold and seasonal freeze-thaw cycles may alter nanoparticle stability, dispersion, and performance. In vitro analysis should be done prior to the modelling. Moreover, dose response modelling should be done because there is no data available for dose response framework for chitosan-based AMR mitigation in Arctic wastewater, aquaculture, or marine systems. Future research should quantify effective dosing ranges, degradation rates, and long-term ecological interactions to support safe application. In addition, small scale pilot trials need to be conducted (including monitoring protocols, community engagement, and cross-sector collaboration) which should validate feasibility, operational practicality, and environmental compatibility.

Future implantation must be guided by Indigenous governance principles. Research should explore culturally grounded decision-making, community consent processes, and integration of Indigenous environmental stewardship within Blue Economy innovation pathways. Economic models are needed to evaluate cost–benefit ratios, circular-economy value creation, and long-term sustainability. This includes assessing how waste-to-value systems can support local employment, diversify fisheries economies, and align with Arctic development priorities.

Many Arctic regions have lack laboratory capacity, processing facilities, and waste-handling infrastructure required for chitosan extraction and nanoparticle formulation. Future work should explore modular, low-energy, community-scale processing systems. Seasonal accessibility should be monitored and evaluated to determine how these seasonal constraints affect production, deployment, monitoring, and supply chains. Transport across remote Arctic regions can be challenging due cost. Future studies evaluate decentralised production models, localised processing hubs, and low-transport deployment strategies.

Together, these gaps define the next steps needed to move from conceptual feasibility to responsible, community-aligned, and environmentally safe implementation in the Arctic.

Conclusion

Climate-linked AMR is an urgent and growing threat, not only for the Arctic region but also globally. This influences by warming temperatures, shifting ecosystems, and increased human activity. Addressing this challenge requires solutions that are both scientifically and environmentally responsible. Chitosan derived from crustacean's waste valorisation streams work as a suitable candidate due to its antimicrobial properties, biodegradability, and compatibility with Arctic ecological conditions.

Framing this approach within the Blue Economy and Triple Bottom Line perspectives demonstrates how environmental protection, community wellbeing, and circular-economy value creation can reinforce one another. By transforming waste into a functional biomaterial, the intervention aligns with sustainable development priorities while offering numerous social and economic benefits for Arctic communities.

However, feasibility remains central. Real-world implementation depends on infrastructure capacity, seasonal accessibility, transport logistics, regulatory permitting, and meaningful Indigenous governance. These factors define the boundary conditions for responsible deployment and highlight the need for coordinated cross-sector collaboration.

The pathway forward involves targeted research, pilot trials, community-driven governance, and continued exploration of waste-to-value innovation. With careful development, chitosan-based approaches can contribute to a resilient, sustainable, and healthy Arctic future.

References

Ahmed, Md. S., Rafi, Md. O. S., & Muslim, T. (2026). Valorization of crab shell waste into chitin, chitosan, and carboxymethyl chitosan: Extraction, chemical modification, and characterization. *Next Materials*, *11*, 101710. https://doi.org/10.1016/j.nxmate.2026.101710

Aslam, B., & Aljasir, S. F. (2025). Climate Change and AMR: Interconnected Threats and One Health Solutions. *Antibiotics*, *14*(9), 946. https://doi.org/10.3390/antibiotics14090946

B. A, C., M H, H., S. M, A., & k, P. (2026). Chitosan-based metal organic frameworks: Promising materials for environmental and biomedical applications. *Next Materials*, *13*, 102504. https://doi.org/10.1016/j.nxmate.2026.102504

Barikani, M., Oliaei, E., Seddiqi, H., & Honarkar, H. (2014). Preparation and application of chitin and its derivatives: a review. *Iranian Polymer Journal*, *23*(4), 307–326. https://doi.org/10.1007/s13726-014-0225-z

Basit, A., Akhtar, M. R., Humza, M., Asad, M., Liu, T.-X., & Hou, Y. (2026). Emerging trends in functional chitosan-based composites: applications in environmental remediation, energy storage, and biomedical solutions. *Journal of Advanced Research*. https://doi.org/10.1016/j.jare.2026.05.044

chemicalresearch. (2026). Top 10 Companies in the Chitosan Market (2026): Market Leaders Driving Global Innovation.

Dadgostar, P. (2019). Antimicrobial Resistance: Implications and Costs . *Infection and Drug Resistance*, *Volume 12*, 3903–3910. https://doi.org/10.2147/IDR.S234610

Depta, J., & Niedźwiedzka-Rystwej, P. (2023). The Phenomenon of Antibiotic Resistance in the Polar Regions: An Overview of the Global Problem. *Infection and Drug Resistance*, *Volume 16*, 1979–1995. https://doi.org/10.2147/IDR.S369023

Dhlamini, K. S., Selepe, C. T., Ramalapa, B., Tshweu, L., & Ray, S. S. (2024). Reimagining Chitosan-Based Antimicrobial Biomaterials to Mitigate Antibiotic Resistance and Alleviate Antibiotic Overuse: A Review. *Macromolecular Materials and Engineering*, *309*(9). https://doi.org/10.1002/mame.202400018

Erta Kalanxh. (2026). *Climate change and antimicrobial resistance*.

FNU Nahiduzzaman. (2026). *Unraveling the potential impact of climate change on the evolution and acceleration of antimicrobial resistance: mechanisms, consequences, and control strategies*.

Food & Beverages. (2026). Crustacean Market Size, Share, Growth and Industry Analysis, By Types (Shrimp, Lobsters, Barnacles), By Applications (Surper Market, Distributor, On-Line Shopping), Regional Insights and Forecast to 2035.

Guo, J., Aroney, S. T. N., Domínguez-Huerta, G., Smith, D., Vik, D., Owusu-Ansah, C., Pratama, A. A., Solonenko, S., Tian, F., Howard-Varona, C., Zhong, Z.-P., Fofana, A., Smith, G. J., Hodgkins, S. B., Cronin, D., Anderson, D., Bennett, K., Dominguez, S., Fahnestock, M. F., … Bagby, S. C. (2026). Mobile genetic elements shape microbial diversity and functions in thawing permafrost soils. *Nature Microbiology*, *11*(7), 1800–1814. https://doi.org/10.1038/s41564-026-02391-7

Haan, T. J., & Drown, D. M. (2021). Unearthing Antibiotic Resistance Associated with Disturbance-Induced Permafrost Thaw in Interior Alaska. *Microorganisms*, *9*(1), 116. https://doi.org/10.3390/microorganisms9010116

Heesoo Kim. (2022). *Characterization of antimicrobial resistance genes and virulence factor genes in an Arctic permafrost region revealed by metagenomics*. https://doi.org/10.1016/j.envpol.2021.118634

Khalid, S., Sabir, S. M., Shahida, S., Khan, G.-L., Siddique, S., Sher, F., Khan, M. I., & Luque, R. (2026). Exploring the multifaceted potential of chitosan-capped silver nanoaprticles: Antioxidant, antimicrobial and antidiabetic properties. Results in Engineering, 30, 110480. https://doi.org/10.1016/j.rineng.2026.110480

Li, W., Yan, D., Weng, B., & Zhu, L. (2023). Research progress on hydrological effects of permafrost degradation in the Northern Hemisphere. *Geoderma*, *438*, 116629. https://doi.org/10.1016/j.geoderma.2023.116629

Lv, J., Lv, X., Ma, M., Oh, D. H., Jiang, Z., & Fu, X. (2023). Chitin and chitin-based biomaterials: A review of advances in processing and food applications. In *Carbohydrate Polymers* (Vol. 299). Elsevier Ltd. https://doi.org/10.1016/j.carbpol.2022.120142

Makowska-Zawierucha, N., Trzebny, A., Zawierucha, K., Manthapuri, V., Bradley, J. A., & Pruden, A. (2024). Arctic plasmidome analysis reveals distinct relationships among associated antimicrobial resistance genes and virulence genes along anthropogenic gradients. *Global Change Biology*, *30*(5). https://doi.org/10.1111/gcb.17293

Matthes, H., Rinke, A., & Dethloff, K. (2015). Recent changes in Arctic temperature extremes: warm and cold spells during winter and summer. *Environmental Research Letters*, *10*(11), 114020. https://doi.org/10.1088/1748-9326/10/11/114020

McCann, C. M., Christgen, B., Roberts, J. A., Su, J.-Q., Arnold, K. E., Gray, N. D., Zhu, Y.-G., & Graham, D. W. (2019). Understanding drivers of antibiotic resistance genes in High Arctic soil ecosystems. *Environment International*, *125*, 497–504. https://doi.org/10.1016/j.envint.2019.01.034

Michael. (2015). *Emerging Issues in Antimicrobial Resistance of Bacteria from Food-Producing Animals. Future Microbiology.*

Rantanen, M. (2022). *The Arctic has warmed nearly four times faster than the globe since 1979*.

Ren, Z., & Gao, H. (2024). Antibiotic resistance genes in integrated surface ice, cryoconite, and glacier-fed stream in a mountain glacier in Central Asia. *Environment International*, *184*, 108482. https://doi.org/10.1016/j.envint.2024.108482

Shu, Q., Gao, H., Li, R., Chen, H., & Na, G. (2024). The source and dissemination of ARGs in pristine environments: Elucidating the role of migratory birds in the Arctic. *Journal of Hazardous Materials*, *480*, 136272. https://doi.org/10.1016/j.jhazmat.2024.136272

Sinha, S., & U. L. S. B. (2025). (n.d.). *Understanding antimicrobial resistance (AMR) mechanisms and advancements in AMR diagnostics. Diagnostic Microbiology and Infectious Disease, 113(2), 116949.*

Vidal, J. L., Jin, T., Lam, E., Kerton, F., & Moores, A. (2022). Blue is the new green: Valorization of crustacean waste. *Current Research in Green and Sustainable Chemistry*, *5*, 100330. https://doi.org/10.1016/j.crgsc.2022.100330

Watts, J., Schreier, H., Lanska, L., & Hale, M. (2017). The Rising Tide of Antimicrobial Resistance in Aquaculture: Sources, Sinks and Solutions. *Marine Drugs*, *15*(6), 158. https://doi.org/10.3390/md15060158

Wenhai, L., Cusack, C., Baker, M., Tao, W., Mingbao, C., Paige, K., Xiaofan, Z., Levin, L., Escobar, E., Amon, D., Yue, Y., Reitz, A., Neves, A. A. S., O'Rourke, E., Mannarini, G., Pearlman, J., Tinker, J., Horsburgh, K. J., Lehodey, P., … Yufeng, Y. (2019). Successful Blue Economy Examples With an Emphasis on International Perspectives. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00261

Wu, R., Trubl, G., Taş, N., & Jansson, J. K. (2022). Permafrost as a potential pathogen reservoir. *One Earth*, *5*(4), 351–360. https://doi.org/10.1016/j.oneear.2022.03.010

Yan, D., Li, Y., Liu, Y., Li, N., Zhang, X., & Yan, C. (2021). Antimicrobial Properties of Chitosan and Chitosan Derivatives in the Treatment of Enteric Infections. *Molecules*, *26*(23), 7136. https://doi.org/10.3390/molecules26237136

Ying, H., Zhang, Y., Hu, W., Wu, W., & Mao, G. (2025). Glaciers as reservoirs of antibiotic resistance genes: hidden risks to human and ecosystem health in a warming world. *Biocontaminant*, *1*(1), 0–0. https://doi.org/10.48130/biocontam-0025-0022

Zhang, B., Zhang, B., Xu, Y., Yan, X., Wang, S., Yang, X., Yang, H., Zhang, G., Zhang, W., Chen, T., & Liu, G. (2024). Shift in potential pathogenic bacteria during permafrost degradation on the Qinghai-Tibet Plateau. *Science of The Total Environment*, *954*, 176778. https://doi.org/10.1016/j.scitotenv.2024.176778

Zhang, T., Barry, R. G., Knowles, K., Heginbottom, J. A., & Brown, J. (2008). Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere. *Polar Geography*, *31*(1–2), 47–68. https://doi.org/10.1080/10889370802175895