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Minimax Optimization and Decision-Making in Therapeutic Human-Body Cooling and Cryogenic Technologies: A Patent Landscape Analysis

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Abstract
Technological development in human-body cooling, preservation, and recovery remains fragmented across medical cooling, cryopreservation, thermal management, and biological applications, leaving innovation opportunities insufficiently defined. This study characterized the patent landscape and identified technological concentrations, gaps, and innovation white spaces to establish development pathways. Patent landscape analysis was conducted using Lens, covering publications from 2000 to September 27, 2026; records were searched, filtered, consolidated by Simple Patent Family, and analyzed using temporal, CPC, applicant, owner, inventor, jurisdictional, patent-type, and citation indicators. Novel findings revealed renewed activity after 2016, concentration in medical cooling and therapeutic thermal-management technologies, U.S. dominance, and an uneven continuum from preservation to rewarming and recovery. Innovation white spaces emerged in preservation–rewarming–recovery systems, cryogenic preservation with controlled rewarming, intelligent closed-loop thermal management, and preservation-oriented applications beyond established contexts. These findings informed the Technology Innovation Pathways Framework, supporting SDGs 3, 9, and 17 through health innovation, development, and interdisciplinary collaboration.

Keywords: Human-body preservation; Refrigeration; Cooling technologies; Cryogenic technology; Patent landscape analysis

Introduction

Temperature-based preservation technologies have become increasingly important in biomedical science because controlled reduction of temperature can suppress metabolism, reduce oxygen demand, and influence physiological responses to severe biological stress. Technologies involving controlled cooling, deep cooling, deep hypothermia, therapeutic hypothermia, induced hypothermia, cryogenic exposure, and cryopreservation have expanded the technological possibilities for temporarily reducing metabolic activity and preserving biological function. In particular, low-temperature approaches have been explored in relation to metabolic suppression, biological preservation, prolonged survival, and the broader concepts of suspended animation and biostasis. Cryopreservation has further extended the technological range toward extremely low temperatures, although preservation of complex biological systems remains challenging because of ice formation, cryoprotectant toxicity, and thermal heterogeneity (Criswell et al., 2023; Pan et al., 2024). These developments demonstrate that temperature-based preservation is no longer limited to conventional refrigeration but represents a multidisciplinary technological domain involving thermal management, cryobiology, physiological monitoring, metabolic regulation, and biomedical engineering. Consequently, understanding how these technologies have evolved is important for identifying technological directions for preserving living human biological function.

In the Philippine context, patent landscape analysis remains an emerging approach for examining technological development, innovation concentration, and opportunities for research and commercialization. Although the local literature remains relatively limited, Philippine-authored studies have begun applying patent intelligence across different technological fields. For example, Gudelos (2025a) used Lens patent data to examine nanotechnology-driven drug delivery systems for Huntington's disease, while another study examined patent trends and innovation ecosystems in reverse-aging technologies (Gudelos, 2025b). More recently, Gudelos et al. (2026) applied patent landscape analysis to fermented food innovations for gut health, identifying technology gaps, white spaces, and potential innovation pathways. These local applications are consistent with the broader literature, which recognizes patent landscape analysis as a systematic approach for mapping technology fields, identifying technological trends and research gaps, and informing research and innovation priorities (Abood & Feltenberger, 2018; van Rijn & Timmis, 2023). Despite these emerging applications, patent landscaping focused specifically on refrigeration, controlled cooling, and cryogenic technologies associated with human-body preservation and recovery remains limited in the Philippine research context. This gap is relevant to a geographically distributed health system in which technologies capable of maintaining biological viability

and extending the time available for medical intervention may have potential value. Philippine literature has documented challenges surrounding organ donation and transplantation, including the relatively limited contribution of deceased donors; Suguitan et al. (2014), for example, reported that deceased organ donation accounted for approximately 20% of kidney transplantation during the period examined, while Pizarra (2025) discussed continuing policy, infrastructural, legal, cultural, and educational considerations surrounding organ donation. Although these studies concern organ donation rather than therapeutic cooling, they provide broader context for examining technologies that may extend biological viability when immediate medical intervention is constrained.

Despite substantial scientific and technological development in controlled cooling, deep hypothermia, therapeutic and induced hypothermia, cryogenic technologies, and cryopreservation, available evidence remains distributed across different technological domains rather than organized into a comprehensive patent-based perspective focused specifically on living human-body preservation through temperature-mediated metabolic suppression. Existing research demonstrates the potential of low-temperature exposure to reduce metabolic activity and preserve biological function, while continuing challenges include maintaining biological viability, controlling thermal conditions, extending preservation duration, and achieving reliable preservation of complex biological systems (Criswell et al., 2023; Pan et al., 2024). This creates a need to examine not only which technologies have been developed but also where patenting activity is concentrated, which technological domains are interconnected, which actors and jurisdictions dominate development, and which technological combinations remain relatively underrepresented. The present study addresses this need through a systematic patent landscape analysis using Lens, with patent-family consolidation and integrated analysis of temporal trends, CPC classifications, applicants, owners, inventors, jurisdictions, patent types, and citations. The methodological design specifically focused on inventions involving living human systems in which controlled cooling, deep cooling, deep hypothermia, therapeutic hypothermia, induced hypothermia, cryogenic technology, or cryopreservation was meaningfully associated with metabolic suppression, metabolic rate, metabolic activity, biological preservation, prolonged survival, suspended animation, or biostasis. By identifying technological concentrations alongside potential gaps and innovation white spaces, the study seeks to establish an integrated evidence base for understanding the technological development of temperature-mediated preservation of living human biological function. Patent landscape analysis is particularly suited to this purpose because it can reveal technological trajectories, concentrations, actors, and emerging opportunity areas that may not be apparent from conventional literature-based assessment alone (Grant et al., 2014; Kortov et al., 2017; van Rijn & Timmis, 2023).

The principal output of the study is therefore the proposed Technology Innovation Pathways Framework (TIPF), which translates identified technological concentrations, gaps, and innovation white spaces into an iterative pathway for future development of temperature-based human-body preservation technologies. Specifically, the study aims to: (1) characterize the patent landscape of refrigeration, cooling, and cryogenic technologies for human-body preservation and recovery in terms of temporal trends, technological classifications, patent applicants and owners, inventors, jurisdictions, patent types, and citation patterns and examine the dominant technological approaches and areas of concentration within the patent landscape; (2) identify technology gaps and potential innovation white spaces based on areas of limited representation, technological concentration, or insufficient integration; and (3) develop a Technology Innovation Pathways Framework that translates these evidence-informed gaps and white spaces into potential pathways for technology development, integration, validation, intellectual-property development, technology transfer, and commercialization. The framework is anchored on the study's focus on the controlled reduction of temperature as a technological means of suppressing metabolism and preserving living human biological function. The study therefore moves beyond mapping existing patents toward an evidence-informed innovation architecture that can guide researchers, engineers, universities, technology-transfer offices, and technology developers in examining how refrigeration, cooling, deep hypothermia, cryogenic technologies, metabolic suppression, biological preservation, prolonged survival, suspended animation, and biostasis may constitute interconnected pathways for future technological development.

METHODS

Research Design

This study employed a patent landscape analysis using a systematic, technology-oriented approach to characterize the development of refrigeration, cooling, and cryogenic technologies associated with human-body preservation and recovery. The analysis integrated bibliographic, technological, ownership, inventor, jurisdictional, citation, and patent-classification indicators to identify patterns of technological development and concentration. Beyond describing patenting activity, the study aimed to identify technology gaps, innovation white spaces, and potential innovation pathways within the field. The analytical unit was the simple patent family, allowing related patent documents associated with the same underlying invention to be consolidated and reducing duplication arising from multiple jurisdictional filings.

Data Source

Patent records were retrieved from the Lens Patents database, a publicly accessible patent information platform that provides bibliographic records, patent families, classifications, citations, applicants or owners, inventors, and related patent information. The search was conducted on September 27, 2026, and covered patent publications dated January 1,

2000 to September 27, 2026. No jurisdictional restriction was initially imposed so that the analysis could capture the international development and geographical distribution of technologies. Both patent applications and granted patents were retained to capture technological activity across different stages of the patenting process.

Search Strategy

A progressive Boolean search strategy was developed to balance search sensitivity with technological relevance. The search was conducted in successive conceptual stages. First, cooling-related technologies were identified using the terms refrigeration, cooling, cryogenic, and hypothermia, producing 7,886,967 records. The concept of a living human target was subsequently incorporated using "human body," "living human," and "living body," reducing the retrieval to 207,081 records. A third concept incorporated preservation- and recovery-related terms, including preservation, metabolic suppression, metabolic rate, suspended animation, biostasis, and recovery, producing 51,915 records. These progressively refined searches were used to identify terminology and concepts that could improve the specificity of the final search.

The final candidate search emphasized specific cooling and hypothermia technologies and biological preservation mechanisms while explicitly excluding technologies directed toward deceased human remains. The final Boolean concept was:

("controlled cooling" OR "deep cooling" OR "deep hypothermia" OR "therapeutic hypothermia" OR "induced hypothermia" OR cryogenic OR cryopreservation) AND ("human body" OR "living human" OR "living body") AND ("metabolic suppression" OR "metabolic rate" OR "metabolic activity" OR "biological preservation" OR "prolonged survival" OR "suspended animation" OR biostasis) NOT (corpse OR cadaver OR "dead body" OR "human remains" OR funeral OR coffin)

This search retrieved 1,587 patent records and served as the final candidate dataset for subsequent filtering, family consolidation, and relevance screening.

Eligibility Criteria

Eligibility criteria were established to ensure that the final dataset represented the technological scope of living human-body cooling for preservation or recovery, rather than general refrigeration or unrelated medical cooling. Records were included when the invention involved a living human, patient, or human biological system, and when cooling, hypothermia, refrigeration, cryogenic technology, or controlled low-temperature exposure constituted a meaningful component of the invention. Technologies were considered relevant when cooling was associated with metabolic suppression, preservation of biological function, prolonged viability or survival, suspended animation, biostasis, or recovery-related applications.

Records were excluded when they primarily concerned corpses, cadavers, dead bodies, human remains, funeral preservation, coffins, food or beverage refrigeration, industrial or building cooling, air-conditioning systems, unrelated specimen storage or transportation, pharmaceutical cold storage without a living-human cooling application, or medical technologies in which cooling was incidental rather than technologically central. Where relevance could not be established from the title or abstract, the claims and available patent information were examined before a final inclusion decision was made.

CPC Classification Analysis

CPC classification was deliberately not applied as an initial retrieval restriction. This methodological decision was based on the interdisciplinary nature of the study. Technologies involving human-body cooling may be classified under medical devices, thermal-management systems, biological preservation, therapeutic applications, or other technological domains. Applying a narrow CPC filter during the initial search could therefore reduce recall and exclude relevant inventions whose principal classification does not explicitly identify cooling or preservation as the primary technological feature.

Instead, CPC classifications were examined after retrieval, filtering, family consolidation, and relevance screening. This post-retrieval approach allowed the classification structure to be used as an analytical indicator of the technological composition of the landscape rather than as a predetermined constraint on the dataset. Particular attention was given to CPC groups directly associated with human thermal management and biological preservation, including A61F7/12 for devices involving heating or cooling of internal body cavities, A61F7/123 and related A61F2007/* subclasses associated with thermal-management technologies, and A01N1/10–A01N1/16 related to preservation of biological material. Pharmaceutical, genetic, biological, and unrelated secondary classifications were not treated as core inclusion classifications unless the associated patent also satisfied the study's technological eligibility criteria.

Data Filtering and Cleaning

The initial 1,587 records were subjected to sequential filtering within Lens. Restricting the publication period to January 1, 2000–September 27, 2026 reduced the dataset to 1,564 records. All jurisdictions were retained. Restriction to patent applications and granted patents produced 1,552 records, while retaining all available languages maintained the same number. CPC/IPC classifications were not restricted during this stage, resulting in 1,552 records. The records were subsequently grouped by Simple Patent Family, reducing the dataset to 517 patent families. A further availability filter identifying records with title, abstract, or claim information produced 512 records suitable for detailed relevance screening.

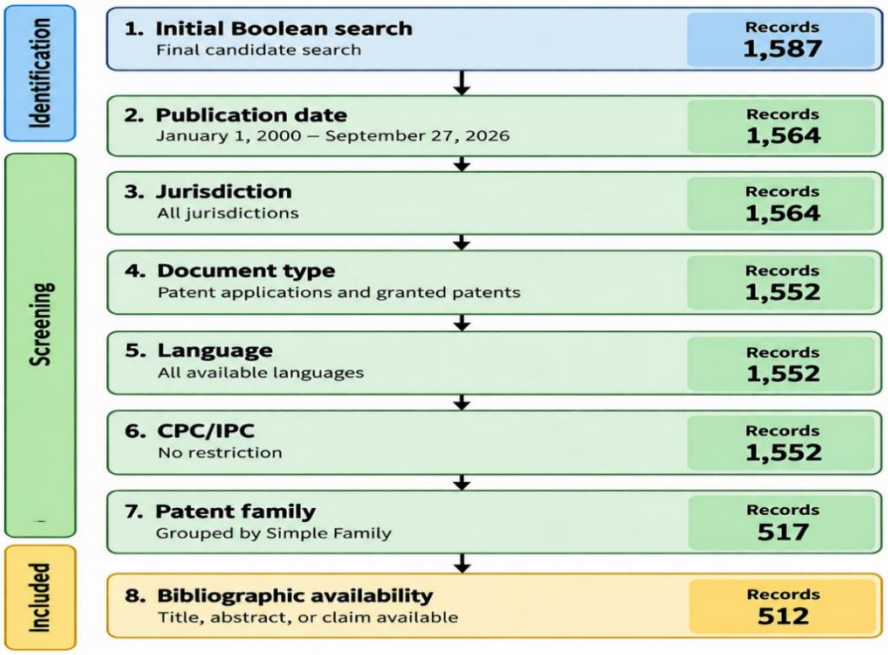
The resulting records were then examined using title, abstract, and claims, with additional patent information consulted when the relevance of an invention remained uncertain. Lens tags and screening notes were used to distinguish records that were included, excluded, or unclear during the relevance assessment. Exclusion decisions were based on the predefined eligibility criteria rather than solely on CPC classification.

Patent Family Consolidation and Screening

Simple-family grouping was used to minimize duplication arising from the filing of substantially related inventions across multiple jurisdictions. This approach allowed the landscape to be interpreted at the level of underlying inventions rather than treating each national or international publication as an independent technological contribution. The family-level dataset was subsequently screened for relevance to the defined research scope. Particular attention was given to the relationship between the cooling intervention, the living-human target, and the preservation or recovery objective. Patents were retained when these three elements were sufficiently connected within the disclosed invention.

PRISMA-Based Documentation of Selection

The identification, filtering, consolidation, and screening stages were documented using a PRISMA flow diagram to provide a transparent representation of the study-selection process. The diagram presents the progression from the initial Boolean search through date and document-type filtering, simple-family consolidation, information-availability filtering, and final relevance assessment.



Note. Patent data were obtained from the Lens patent database, with the figure enhanced using generative AI for improved visual presentation.

Figure 1. PRISMA Flow Diagram of the Patent Selection and Screening Process Patent Landscape Analysis

The final screened dataset was analyzed using multiple complementary indicators. Publication trends were examined to characterize changes in patenting activity over time. Patent owners were analyzed to identify organizations with substantial patent portfolios, while inventor analysis was used to identify recurring individual contributors. Jurisdictional analysis was conducted to examine geographical concentrations of patenting activity, and document-type analysis distinguished patent applications from granted patents. Citation analysis was used to identify highly cited patent families and potentially influential technological disclosures. CPC analysis was conducted to characterize the technological domains represented within the patent landscape.

These indicators were interpreted collectively rather than independently. For example, owner and inventor distributions were examined alongside CPC classifications to determine whether particular organizations or inventors were associated with specific technological approaches. Similarly, temporal and jurisdictional patterns were considered when interpreting the emergence and geographical concentration of technological activity. This integrated approach provided a more comprehensive representation of the development and structure of the technology field.

Identification of Technology Gaps and Innovation White Spaces

Technology gaps were identified by examining areas in which the existing patent landscape showed limited representation, technological concentration, or insufficient diversification relative to the broader research concept. Particular attention was given to underrepresented cooling approaches, preservation mechanisms, human-body applications, and technology combinations. The analysis distinguished between areas with extensive patent activity and areas characterized by relatively sparse technological representation.

Innovation white spaces were subsequently identified as potentially promising areas located at the intersection of relevant technological needs and limited patent concentration. White-space identification was not interpreted as proof that no invention exists in a particular area; rather, it represented an analytical indication of relatively limited patent activity within the defined search and screening boundaries. These findings were used to generate potential directions for future research, technology development, and patent-oriented innovation.

Development of the Technology Innovation Framework

The findings from the patent landscape analysis were synthesized into a Technology Innovation Framework for refrigeration, cooling, and cryogenic technologies for human-body preservation and recovery. The framework integrated dominant technological approaches, emerging areas, patent ownership patterns, technological classifications, and identified gaps and white spaces. It was designed to connect the observed patent landscape with potential future innovation pathways while distinguishing established technological domains from areas requiring further investigation.

Ethical Considerations

This study involved the analysis of publicly accessible patent records and did not involve human participants, human biological specimens, animals, clinical records, or personally identifiable participant information. Consequently, informed consent and human-subject ethical approval were not required. Research integrity was maintained through documentation of the search strategy, eligibility criteria, filtering procedures, family consolidation, screening process, and analytical methods to support transparency and reproducibility.

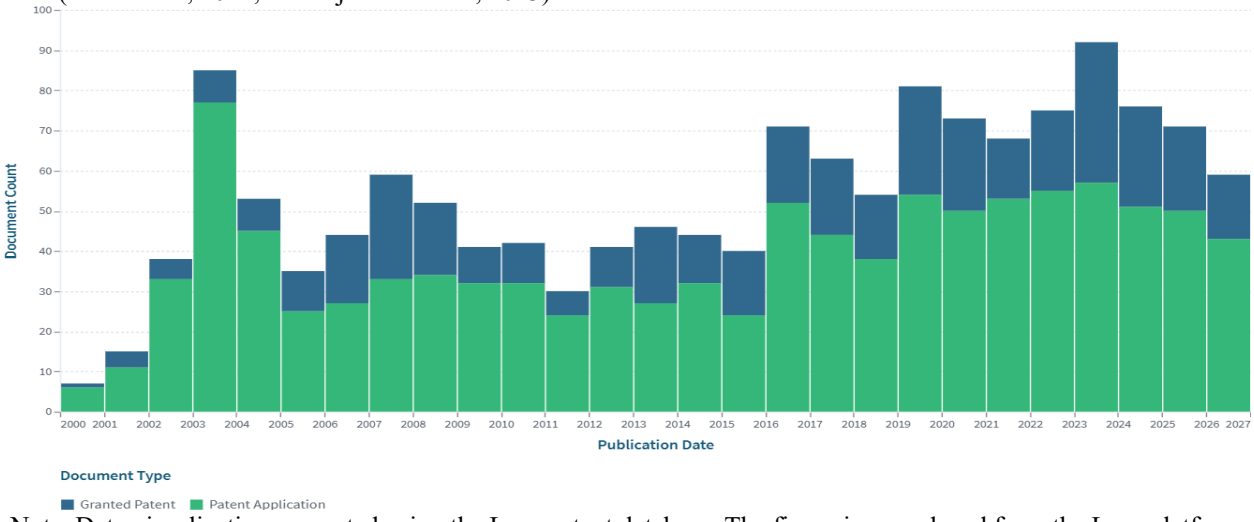
Generative AI tools were used only to support language refinement, organization, visualization enhancement, and presentation of analytical outputs. AI was not used to fabricate patent records, sources, numerical results, or analytical findings. AI-assisted outputs were critically reviewed and validated by the researchers, who retained full responsibility for the accuracy, interpretation, originality, and integrity of the study.

RESULTS AND DISCUSSIONS

The results and discussions present the patent landscape of refrigeration, cooling, and cryogenic technologies for human-body preservation and recovery by examining temporal trends, technological classifications, applicants and ownership, geographic distribution, patent types, inventors, and citation patterns. These findings are subsequently interpreted to identify technological concentrations, gaps, and potential innovation pathways that provide the basis for the proposed Technology Innovation Pathways Framework (TIPF).

Patent Documents Over Time

Figure 2 shows the annual distribution of patent documents related to refrigeration, cooling, and cryogenic technologies for human body preservation and recovery identified in the Lens patent database from 2000 to September 27, 2026. Patent activity was very limited during 2000–2002, increased sharply in 2003–2004, and reached an early peak in 2004 at approximately 85 documents. Activity subsequently fluctuated between 2005 and 2015, generally remaining at moderate levels, before becoming more pronounced from 2016 onward. A second period of stronger activity occurred during 2019–2025, with the highest annual volume appearing in 2024 at approximately 92 documents, followed by a decline in 2025 and 2026. The predominance of patent applications (green) over granted patents (blue) across much of the series further indicates that a substantial portion of the observed activity represents ongoing inventive and intellectual-property development rather than completed grants. Such temporal patent analysis is useful for identifying changes in technological activity and development trajectories within a defined technology field (Grant et al., 2014; van Rijn & Timmis, 2023).



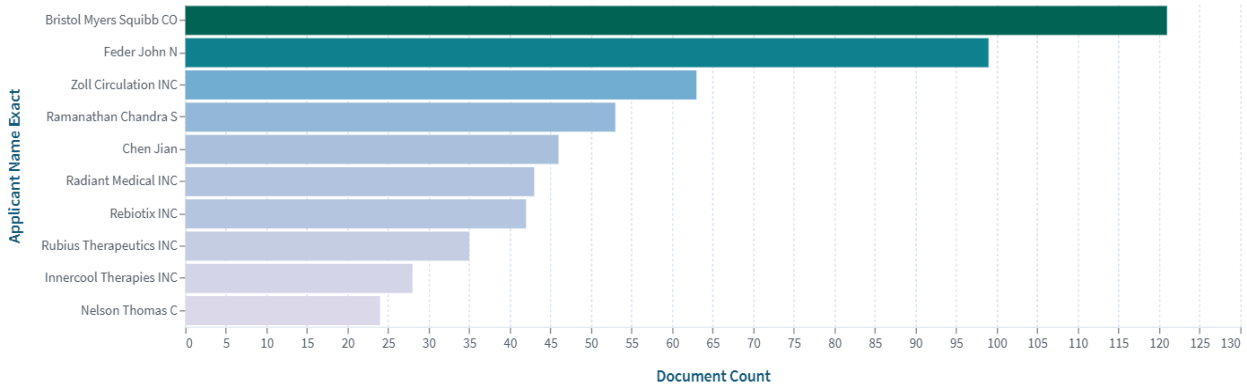
Note. Data visualization generated using the Lens patent database. The figure is reproduced from the Lens platform and is freely accessible for research and academic use.

Figure 2. Patent Documents Over Time for Refrigeration, Cooling, and Cryogenic Technologies for Human Body Preservation and Recovery, 2000–September 27, 2026

The figure's nonlinear trajectory characterized by an early surge, a prolonged period of fluctuation, and renewed growth after 2016 suggests successive phases of inventive activity rather than a continuous expansion of the technology. In the context of human-body preservation and recovery, the renewed activity from 2016 and the high levels observed around 2019–2025 may indicate increasing diversification of low-temperature technologies, including controlled cooling, therapeutic hypothermia, cryogenic approaches, and specialized thermal-management systems. This temporal concentration is analytically important because patent landscapes can reveal technology areas receiving sustained inventive attention and can help identify emerging opportunities and underdeveloped technical spaces (van Rijn & Timmis, 2023); large-scale patent analysis likewise supports the examination of technological development and diffusion over time (Fredström et al., 2021). However, the decline in 2025–2026 should not be interpreted as evidence of declining technological interest because recent patent years may be incomplete due to the approximately 18-month publication interval between patent filing and public disclosure (van Rijn & Timmis, 2023). Overall, the figure indicates a maturing but still fluctuating innovation trajectory, providing a temporal basis for examining which technologies, applicants, and technological gaps are driving the recent concentration of patent activity.

Top Applicants

Figure 3 presents the top applicants contributing patent documents within the patent landscape on refrigeration, cooling, and cryogenic technologies for human body preservation and recovery. The distribution is led by Bristol Myers Squibb Co. with approximately 121 documents, followed by Feder John N. with about 98, while Zoll Circulation Inc. accounts for approximately 63 documents. Other prominent applicants include Ramanathan Chandra S, Chen Jian, Radiant Medical Inc., Rebiotix Inc., Rubius Therapeutics Inc., Innercool Therapies Inc., and Nelson Thomas, with approximately 24–52 documents each. The concentration of documents among a relatively small group of applicants indicates that patenting activity in this technology domain is not evenly distributed, but is instead associated with identifiable organizations and individual applicants. Applicant-level analysis is useful in patent landscaping because it reveals the organizations actively investing in and protecting technological developments within a defined field (van Rijn & Timmis, 2023).



Note. Data visualization generated using the Lens patent database. The figure is reproduced from the Lens platform and is freely accessible for research and academic use.

Figure 3. Patent Documents by Top Applicants in Refrigeration, Cooling, and Cryogenic Technologies for Human Body Preservation and Recovery

The marked difference between the leading applicants and the lower-ranked group suggests concentration of inventive activity around particular technological actors, potentially reflecting accumulated expertise, established research programs, or sustained intellectual-property strategies in medical cooling and related human-preservation technologies. The presence of applicants associated with circulatory support, therapeutic cooling, and biomedical technologies is consistent with the broader landscape in which low-temperature interventions intersect with critical-care, cardiovascular, and biological-preservation applications. However, applicant document counts should not be interpreted directly as measures of technological quality, commercial success, or clinical effectiveness; a higher count may reflect differences in filing strategies, portfolio size, continuation practice, or jurisdictional coverage. Patent landscapes are therefore most informative when applicant concentration is examined together with technology classifications, temporal trends, jurisdictions, and patent families to identify areas of technological specialization and potential innovation gaps (van Rijn & Timmis, 2023; Kortov et al., 2017).

Patent Documents by Jurisdiction

Figure 4 presents the jurisdictional distribution of patent documents identified in the Lens patent landscape for refrigeration, cooling, and cryogenic technologies for human body preservation and recovery. The United States accounts for the dominant share of the records, representing approximately 74% of the documents, followed by WO–WIPO records at about 21%, while European patent records comprise approximately 5%. This distribution indicates that the landscape is strongly concentrated in U.S.-associated patent filings, with international PCT/WO filings forming a substantial secondary component. Jurisdictional analysis is analytically important because it provides a spatial dimension of a patent landscape and helps identify where applicants seek intellectual-property protection for emerging technologies

(Grant et al., 2014; van Rijn & Timmis, 2023).

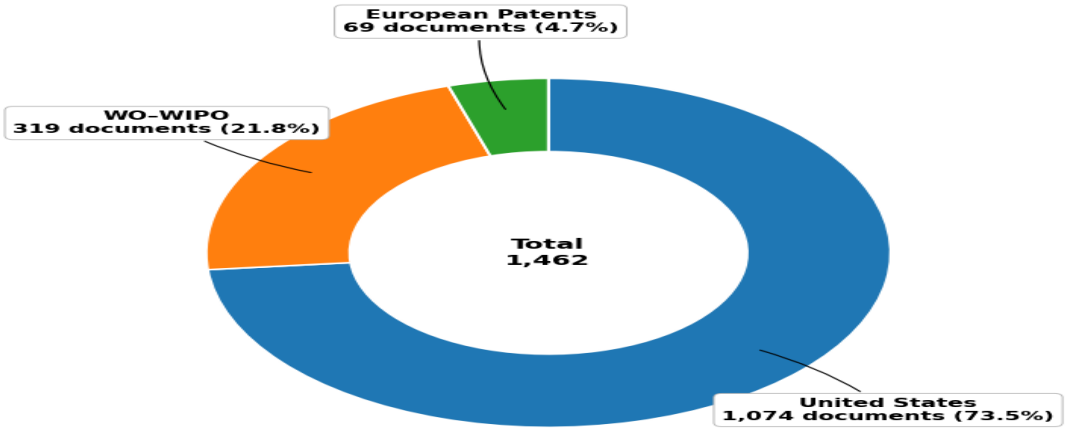
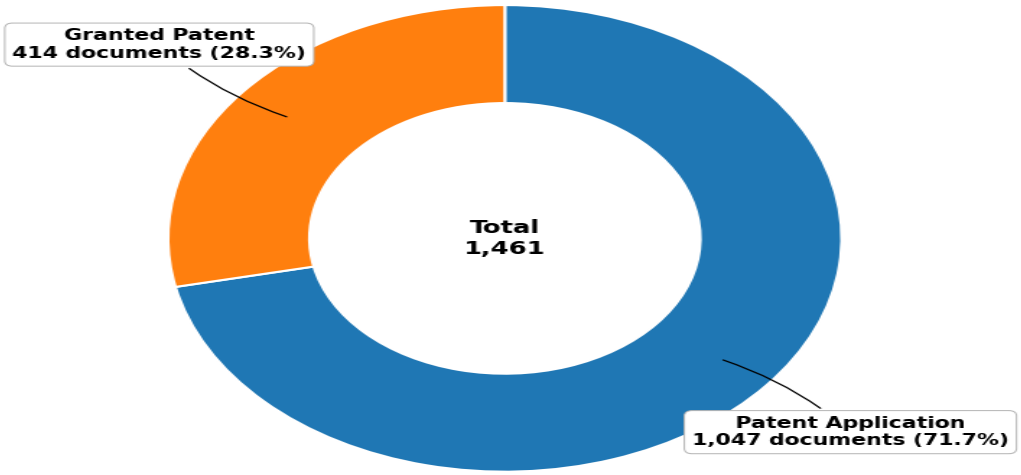


Figure 4. Patent Documents by Jurisdiction for Refrigeration, Cooling, and Cryogenic Technologies for Human Body Preservation and Recovery

The pronounced U.S. share suggests that the United States is a major patenting and protection venue within this technology landscape, potentially reflecting the concentration of biomedical innovation, clinical technology development, and commercialization activities in the jurisdiction. The substantial WO–WIPO component is also important because international applications can signal an intention to preserve options for protection across multiple national markets, although a WO filing should not be interpreted as equivalent to a granted patent in a particular country. The relatively smaller European share further demonstrates that patent activity is spatially uneven rather than uniformly distributed across major patent systems. Nevertheless, jurisdictional counts alone cannot establish technological leadership or market success because filing strategies, patent-office practices, applicant preferences, and international extension decisions influence the observed distribution; therefore, these results should be interpreted alongside applicant, technology-classification, patent-family, and temporal analyses (Grant et al., 2014; van Rijn & Timmis, 2023).

Patent Documents by Type

Figure 5 shows the distribution of patent documents by type within the landscape of refrigeration, cooling, and cryogenic technologies for human body preservation and recovery. Patent applications account for 71.7% of the records, whereas granted patents represent 28.3 %, indicating that the dataset is predominantly composed of published applications rather than completed grants. This distinction is analytically relevant because published applications can provide earlier evidence of inventive activity, while grants represent applications that have progressed through the patent examination process. Chen, Lin, and Huang (2012) emphasized that the relationship between published applications and granted patents can provide information for examining technology-development trends, making the application-to-grant distribution a useful indicator when interpreting the maturity of a patent landscape.



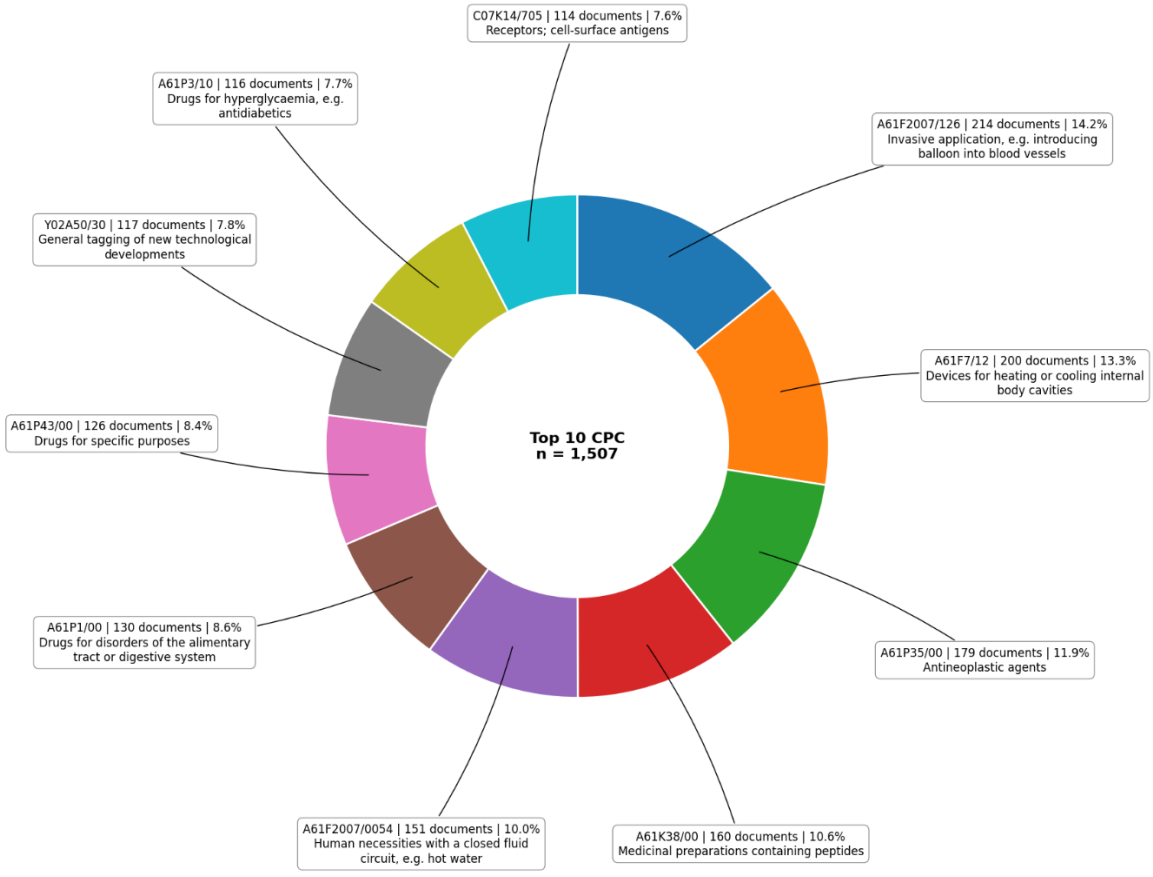
Note. Patent data were obtained from the Lens patent database, with the figure enhanced using generative AI for improved visual presentation.

Figure 5. Patent Documents by Type for Refrigeration, Cooling, and Cryogenic Technologies for Human Body Preservation and Recovery

The predominance of applications suggests that the identified technology field contains substantial ongoing inventive and intellectual-property activity, rather than consisting mainly of technologies that have already reached granted-patent status. In the broader landscape, this pattern is relevant because patent applications can provide insight into technologies that organizations are actively seeking to protect and develop, while the progression from application to grant provides an additional perspective on technological development (Chen et al., 2012; Mejia & Kajikawa, 2025). However, the application-to-grant ratio should not be interpreted as a direct measure of innovation quality or technological success because examination periods, abandonment, continuation procedures, and jurisdictional differences can affect the observed distribution. Thus, Figure 5 is best interpreted together with the temporal, jurisdictional, applicant, and patent-family analyses to provide a more complete picture of the development and protection of human-body cooling and preservation technologies.

Top CPC Classification Codes

Figure 6 presents the distribution of the 10 most frequently occurring CPC classification codes within the patent landscape for refrigeration, cooling, and cryogenic technologies for human body preservation and recovery. The most frequent classification is A61F2007/126 with 214 documents (14.2%), followed by A61F7/12 with 200 (13.3%) and A61P35/00 with 179 (11.9%). Other prominent classifications include A61K38/00 (160; 10.6%), A61F2007/0054 (151; 10.0%), A61P1/00 (130; 8.6%), A61P43/00 (126; 8.4%), Y02A50/30 (117; 7.8%), A61P3/10 (116; 7.7%), and C07K14/705 (114; 7.6%). Collectively, these classifications show that the patent set spans medical cooling devices, invasive or fluid-based systems, therapeutic applications, and biological or pharmaceutical technologies, rather than representing a single technical pathway. CPC-based analysis is valuable in patent landscaping because classification codes provide a structured way to group patents according to technological subject matter and to identify clusters that may not be captured consistently through keywords alone (Adel & Harrison, 2026; Jürgens & Clarke, 2019).



Note. Patent data were obtained from the Lens patent database, with the figure enhanced using generative AI for improved visual presentation.

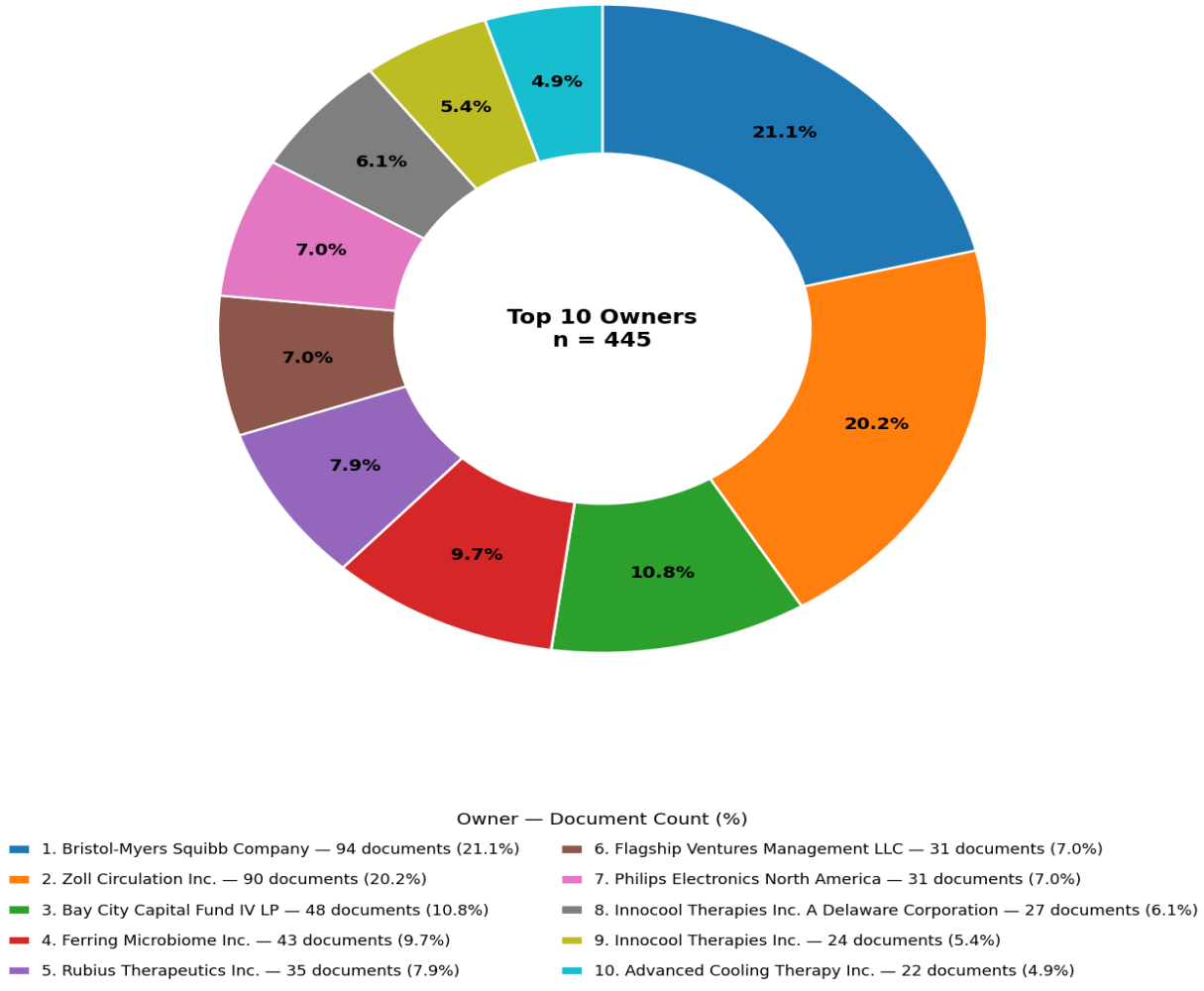
Figure 6. Top CPC Classification Codes in Refrigeration, Cooling, and Cryogenic Technologies for Human Body Preservation and Recovery

The dominant presence of A61F7/12, which covers devices for heating or cooling internal body cavities, together with A61F2007/126 and A61F2007/0054, indicates a substantial technological emphasis on device-based and fluid-mediated approaches to controlling human-body temperature. At the same time, the prominence of A61P and A61K classifications indicates that many documents intersect with therapeutic or biological applications, demonstrating the multidisciplinary character of the landscape. This pattern is analytically important because CPC distributions can reveal the technological

components and application domains surrounding an innovation field and can support subsequent clustering of patents into meaningful technology groups (Adel & Harrison, 2026). However, CPC counts should be interpreted cautiously because a single patent document may receive multiple CPC classifications, meaning that the 1,507 occurrences represented by the top 10 codes do not correspond to 1,507 unique patent documents. The figure therefore represents the frequency of classification assignments, providing a map of technological emphasis rather than a mutually exclusive distribution of inventions.

Top Owners

Figure 7 presents the distribution of the top 10 patent owners identified within the patent landscape for refrigeration, cooling, and cryogenic technologies for human body preservation and recovery. Among the 445 documents represented by the leading owners, Bristol-Myers Squibb Company accounts for the largest share with 94 documents (21.1%), followed by Zoll Circulation Inc. with 90 (20.2%) and Bay City Capital Fund IV LP with 48 (10.8%). Other prominent owners include Ferring Microbiome Inc. (43; 9.7%), Rubius Therapeutics Inc. (35; 7.9%), Flagship Ventures Management LLC and Philips Electronics North America (31 each; 7.0%), Innocool Therapies Inc. A Delaware Corporation (27; 6.1%), Innocool Therapies Inc. (24; 5.4%), and Advanced Cooling Therapy Inc. (22; 4.9%). The concentration of patent documents among identifiable owners provides an actor-level view of the landscape, complementing the temporal, jurisdictional, and technological classification analyses. Patent landscape studies commonly use assignee or owner distributions to identify organizations with substantial patenting activity and to characterize the competitive or technological structure of an emerging field (Mattos & Speziali, 2017; Clarke et al., 2020).



Note. Patent data were obtained from the Lens patent database, with the figure enhanced using generative AI for improved visual presentation.

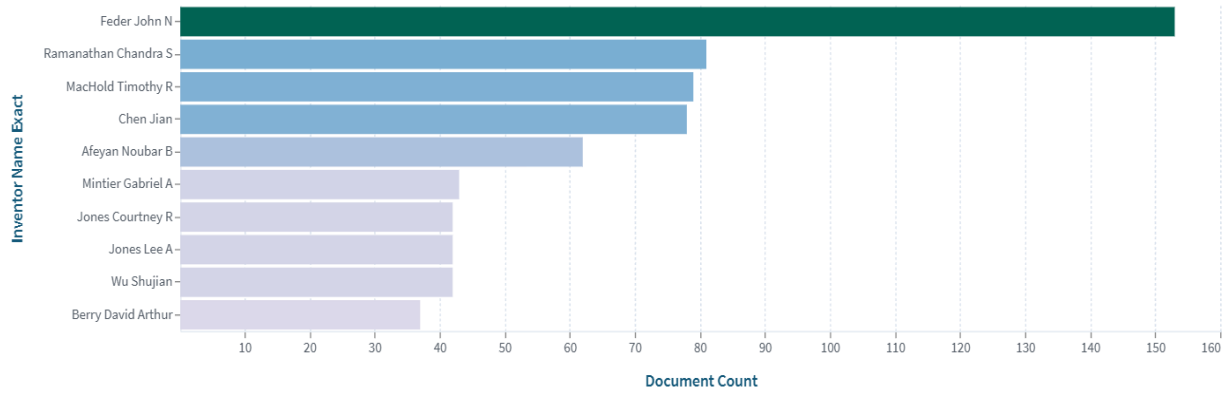
Figure 7. Top Patent Owners in Refrigeration, Cooling, and Cryogenic Technologies for Human Body Preservation and Recovery

The distribution shows that the landscape is not dominated by a single owner, although the first two organizations together account for 41.3% of the documents represented in the top-10 group, indicating substantial concentration among leading actors. The presence of pharmaceutical/biotechnology organizations alongside companies associated with cooling and temperature-management technologies suggests that the innovation space extends beyond standalone cooling equipment toward therapeutic, biological, and integrated medical applications. Thus, owner analysis helps identify the organizations

contributing substantially to the technological development of the field and can reveal whether an emerging technology is being shaped primarily by specialized technology firms, established healthcare companies, or a combination of actors. However, the figure should not be interpreted as a direct measure of technological quality, commercial success, or patent strength; ownership counts can also be affected by portfolio size, corporate restructuring, subsidiary naming, and differences in how assignee names are recorded or harmonized in patent databases.

Top Inventors

Figure 8 presents the top inventors contributing to the patent landscape for refrigeration, cooling, and cryogenic technologies for human body preservation and recovery, based on document counts in the Lens dataset. Feder John N. has the highest inventor-associated count at approximately 153 documents, followed by Ramanathan Chandra S. (81), MacHold Timothy R. (79), and Chen Jian (78). The remaining leading inventors include Afeyan Noubar B. (62), Mintier Gabriel A. (43), Jones Courtney R. (42), Jones Lee A. (42), Wu Shujian (42), and Barry David Arthur (37). The concentration of patent documents among a relatively small group of prolific inventors indicates that individual contributors have played an important role in developing technologies within this landscape. Inventor-level analysis is useful for identifying recurring technical contributors and potential sources of expertise, collaboration, and technological knowledge within a defined patent domain (Bergeaud & Verluise, 2023).



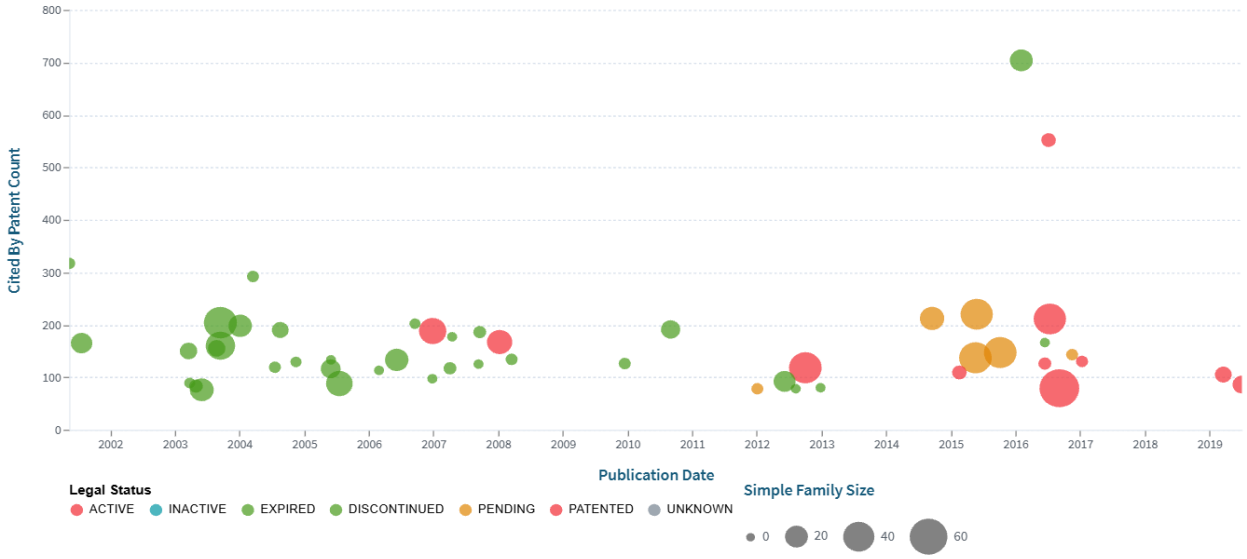
Note. Data visualization generated using the Lens patent database. The figure is reproduced from the Lens platform and is freely accessible for research and academic use.

Figure 8. Top Inventors in Refrigeration, Cooling, and Cryogenic Technologies for Human Body Preservation and Recovery

The marked difference between the leading inventor and the subsequent group suggests that patenting activity is unevenly distributed among individual contributors, which may reflect sustained involvement in particular technological programs, organizations, or patent portfolios. In the context of this landscape, identifying prolific inventors can help connect individual technical expertise with the broader owner and technology-classification patterns, potentially revealing where specialized knowledge is concentrated and where future collaboration or technology development may be occurring. Such inventor-level information complements owner-level analysis because an organization may possess a substantial portfolio while the underlying inventions are concentrated among a smaller number of recurring contributors. However, inventor document counts should not be interpreted as direct measures of individual innovation quality, scientific impact, or technological importance, because patenting practices vary across organizations and a single invention may involve multiple inventors; additionally, differences in name harmonization can affect inventor counts.

Top Cited Patents

Figure 9 presents the distribution of patent citation counts by publication date, with bubble size representing simple family size. The landscape shows substantial variation in citation impact across the identified patents. The most highly cited patent in the figure received approximately 710 citations, followed by another patent with about 550 citations, while several other patents published mainly between the early 2000s and late 2010s accumulated roughly 100–300 citations. The concentration of highly cited patents at particular publication dates suggests that some inventions have become substantially more visible or influential within subsequent technological developments. Forward patent citations are commonly used as an indicator of technological impact because citations reflect the extent to which later patents build upon or reference earlier inventions, although citation counts should be interpreted as indicators rather than direct measures of invention quality or commercial success (Aristodemou & Tietze, 2018; Mariani et al., 2019).



Note. Data visualization generated using the Lens patent database. The figure is reproduced from the Lens platform and is freely accessible for research and academic use.

Figure 9. Top Cited Patents in Refrigeration, Cooling, and Cryogenic Technologies for Human Body Preservation and Recovery

The major pattern indicates that technological influence is concentrated in a relatively small number of patents rather than being evenly distributed across the landscape. This makes citation analysis particularly useful for identifying foundational or repeatedly referenced technologies that may warrant closer examination in subsequent claim, technology-cluster, and innovation-gap analyses. The combination of citation count and simple family size also provides a useful distinction between individual patent records and broader invention families, helping reveal whether highly cited technologies are associated with more extensive patent-family development. However, citation counts are strongly affected by patent age, because older patents have had more time to accumulate forward citations; recent patents may therefore appear less influential simply because insufficient time has elapsed. Citation practices may also vary by patent office and may reflect examiner or applicant citation behavior, so the highly cited patents in Figure 9 should be treated as technological signals requiring qualitative patent-level review, rather than definitive measures of technological importance (Aristodemou & Tietze, 2018; Mariani et al., 2019).

Technology Innovation Gaps and Innovation White-Spaces

The patent landscape demonstrates an expanding but uneven and technologically heterogeneous innovation domain for refrigeration, cooling, and cryogenic technologies associated with therapeutic human-body recovery. Rather than showing a linear maturation pathway, the temporal pattern indicates successive periods of inventive activity: limited activity during 2000–2002, an early increase in 2003–2004, fluctuation through 2005–2015, and renewed activity from 2016 onward, with the strongest concentration during 2019–2025 and approximately 92 documents in 2024. The predominance of patent applications (71.7%) over granted patents (28.3%) further indicates that a substantial portion of the observed activity remains within continuing inventive and intellectual-property development. This pattern is consistent with the use of patent landscapes to identify technological trajectories, emerging areas, and changes in inventive activity over time (Grant et al., 2014; Kortov et al., 2017; van Rijn & Timmis, 2023). Technologically, the landscape is not centered on one homogeneous cooling technology. The dominant CPC classifications include A61F2007/126, A61F7/12, and A61F2007/0054, which collectively indicate substantial activity in human-body temperature-control and cooling technologies, while A61P and A61K classifications demonstrate strong connections with therapeutic, biological, pharmaceutical, and disease-related applications. The combination of these patterns suggests that the field has developed primarily through medical and therapeutic temperature-management applications, with increasing technological convergence across cooling devices, fluid-mediated systems, circulatory support, biological interventions, and related biomedical technologies. Patent classification is particularly useful for this interpretation because classification-based analysis can reveal technological relationships that may not be evident from keyword searching alone (Jürgens & Clarke, 2019; van Rijn & Timmis, 2023). Thus, the principal innovation gap is not simply a lack of patenting, but the uneven integration of technologies across the complete preservation-to-recovery continuum, particularly where controlled cooling must be connected with preservation, physiological monitoring, controlled rewarming, and subsequent recovery. The decline observed in 2025–2026 should also be interpreted cautiously because recently filed patent applications may not yet be publicly visible because of patent publication delays.

Within this broader pattern, several potential technology gaps and innovation white-spaces can be identified, provided that white space is understood as a strategically underrepresented or insufficiently integrated technological area rather than simply an area with few patents. Patent-landscape methodology emphasizes that meaningful interpretation requires consideration of technological clusters, patent families, actors, jurisdictions, temporal activity, and other indicators rather

than relying solely on document counts (Grant et al., 2014; van Rijn & Timmis, 2023). On this basis, (1) integrated preservation–rewarming–recovery systems represent a potential white space. The strong representation of cooling-related CPC classifications demonstrates substantial development of mechanisms for controlling human-body temperature, but the present aggregate results do not show an equivalently prominent technological concentration around an integrated system connecting controlled cooling, preservation, rewarming, and recovery. This suggests an opportunity for integrated platforms incorporating temperature sensors, physiological monitoring, automated thermal control, controlled rewarming, and recovery-oriented assessment. (2) Advanced cryogenic preservation and controlled rewarming constitute another potential gap. Although cryogenic technologies are explicitly represented within the search scope, the dominant classification pattern is more strongly associated with medical cooling and therapeutic temperature management than with a clearly differentiated cryogenic preservation-and-recovery architecture. The opportunity may therefore involve cryogenic temperature uniformity, vitrification-compatible thermal management, cryoprotectant integration, and controlled rewarming technologies; however, these should be regarded as hypothesis-generating opportunities requiring patent-claim review and scientific validation, rather than evidence that such technologies are absent. (3) Intelligent, adaptive, and closed-loop thermal management is another potential white-space direction. The concentration of device-based and fluid-mediated cooling technologies provides evidence of substantial development in temperature-control mechanisms, while the present landscape results do not establish how extensively these technologies are integrated with adaptive physiological sensing, predictive control, or automated individualized cooling and rewarming. Such integration could form a technological pathway toward systems that dynamically modify thermal conditions according to physiological measurements. (4) Preservation-oriented applications extending beyond established therapeutic contexts may also warrant investigation. The landscape is strongly connected to pharmaceutical, biotechnology, circulatory-support, and therapeutic actors, suggesting that much inventive activity has evolved around established medical applications rather than a clearly separated preservation-and-recovery technology platform. These areas should be treated as potential white spaces, because a complete determination would require claim-level analysis, technology matrices, family-level consolidation, and examination of unpublished or differently classified technologies.

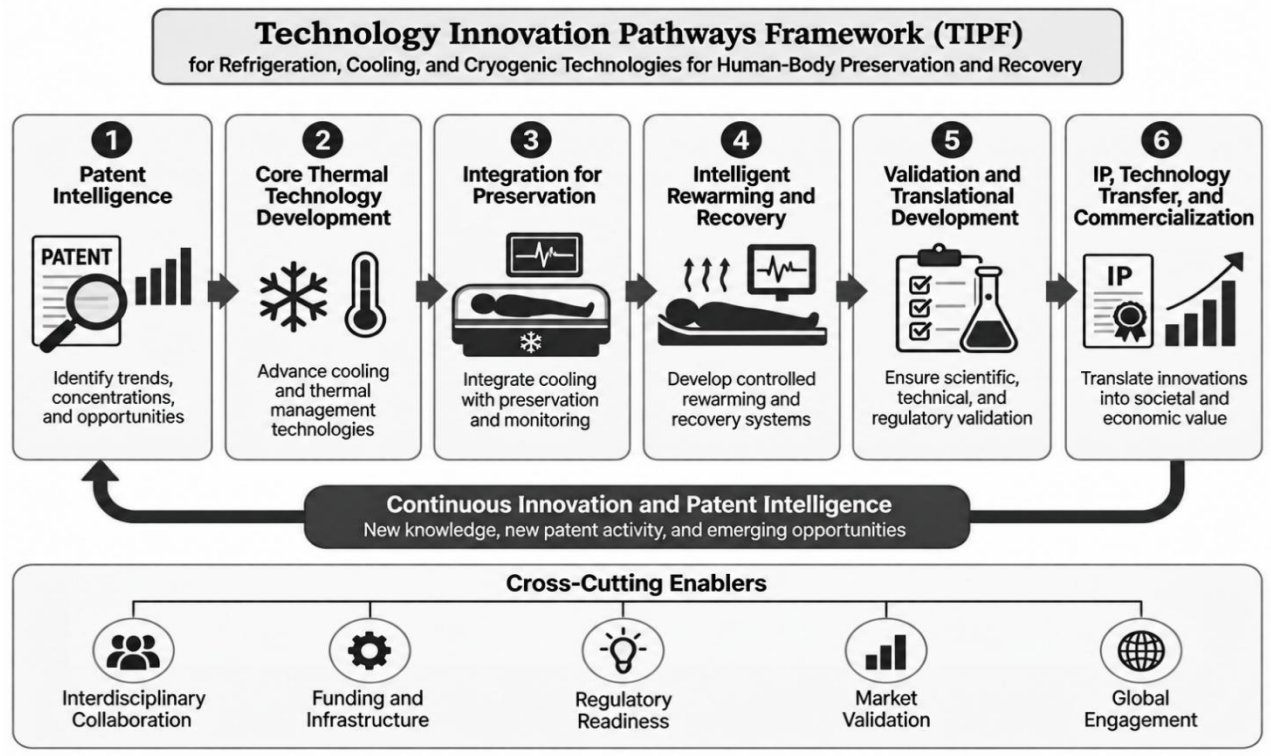
The cross-dimensional evidence further indicates that innovation opportunities may arise from actor concentration, geographic concentration, ownership structure, inventor concentration, and citation influence, rather than technology alone. Applicant activity is concentrated among identifiable actors, with Bristol Myers Squibb Co. accounting for approximately 128 documents, Feder John N. approximately 100, and Zoll Circulation Inc. approximately 63; the leading owner group similarly shows substantial concentration, with Bristol-Myers Squibb and Zoll Circulation together accounting for 41.3% of documents represented among the top 10 owners. Such concentration may indicate accumulated technical expertise, established research programs, and sustained intellectual-property strategies, but patent counts cannot independently establish technological quality or commercial success (Mattos & Speziali, 2017; Kortov et al., 2017). The geographic pattern is similarly uneven: approximately 74% of records are associated with the United States, 21% with WO–WIPO filings, and approximately 5% with European records. This creates a potential geographic and institutional diversification opportunity, particularly for universities, research institutes, technology-transfer offices, and emerging companies that may develop technologies addressing underrepresented applications or markets. The concentration of prolific inventors further suggests that technical knowledge is clustered among recurring contributors, creating potential opportunities for interdisciplinary collaboration and knowledge diffusion. Citation analysis provides another dimension: several older patents have accumulated approximately 100–300 forward citations, while the most highly cited patents in the dataset received approximately 710 and 550 citations. Forward citations can provide useful signals of technological influence, but citation counts are affected by patent age, citation practices, jurisdiction, and other factors; therefore, highly cited patents should be treated as technological signals requiring qualitative examination rather than direct measures of invention quality (Aristodemou & Tietze, 2018; Mariani et al., 2019). Accordingly, the integrated gap/white-space taxonomy emerging from the landscape comprises (1) preservation–rewarming–recovery integration, (2) advanced cryogenic preservation and controlled rewarming, (3) intelligent closed-loop thermal management, (4) expanded preservation-oriented applications, (5) geographic and institutional diversification, and (6) interdisciplinary collaboration and technology-transfer opportunities.

Taken together, these gaps provide the analytical foundation for a technology innovation pathway connecting cooling, preservation, monitoring, rewarming, and recovery, while simultaneously addressing the structural dimensions of ownership, geography, collaboration, intellectual-property strategy, and commercialization. The landscape indicates that the technological field already possesses substantial capabilities in controlled cooling and therapeutic temperature management, but the evidence suggests opportunities to examine how these capabilities could be connected into more comprehensive preservation-and-recovery systems. The predominance of applications, renewed activity after 2016, concentration of technological classifications, and clustering of applicants and owners collectively indicate an active field in which further technological differentiation and integration remain possible. Patent landscapes can support precisely this type of analysis by revealing technological trends, actors, geographic activity, and potential research or innovation gaps (Grant et al., 2014; van Rijn & Timmis, 2023). However, several evidence-based cautions are necessary: low patent activity does not establish absence of innovation; recent patents may have low citation counts simply because insufficient time has passed; inactive, abandoned, or expired patents are not automatically free to use; and apparent white spaces may reflect differences in funding, infrastructure, filing strategies, classification practices, commercialization incentives, or geographic patenting behavior. In addition, patent landscapes do not by themselves establish scientific feasibility, clinical

effectiveness, market viability, regulatory acceptability, or freedom to operate. Therefore, the identified white spaces should function as strategic research and innovation hypotheses that require subsequent patent-claim analysis, scientific and engineering validation, market assessment, regulatory review, and freedom-to-operate analysis before commercialization or patenting decisions are made. This integrated interpretation provides the bridge toward the proposed Technology Innovation Pathways Framework (TIPF), through which identified technological concentrations, gaps, and white spaces are translated into technology integration opportunities, intelligent preservation and recovery strategies, validation pathways, intellectual-property and commercialization strategies, and directions for next-generation innovation.

Technology Innovation Pathways Framework

The proposed Technology Innovation Pathways Framework (TIPF) provides an iterative structure for translating patent-landscape evidence into technological development, validation, and innovation for refrigeration, cooling, and cryogenic technologies for human-body preservation and recovery.



Note. Framework data were derived from the study findings using the Lens patent database. The figure was enhanced with generative AI for illustration and educational purposes only.

Figure 10. Technology Innovation Framework for Refrigeration, Cooling, and Cryogenic Technologies for Human-Body Preservation and Recovery

As illustrated in Figure 10, the framework begins with Pathway 1: Patent Intelligence, which serves as the evidence-generating foundation of the innovation process. The temporal analysis indicates limited patent activity during 2000–2002, an increase during 2003–2004, fluctuations from 2005–2015, and renewed activity from 2016 onward, with particularly strong activity during 2019–2025 and approximately 92 documents in 2024. Patent applications also substantially outnumber granted patents, indicating continuing inventive and filing activity in the field. Accordingly, patent intelligence in the TIPF encompasses temporal trends, CPC/IPC classifications, patent-family structures, applicants, ownership, jurisdictions, and citation patterns. Such multidimensional patent landscaping can reveal technological trajectories, areas of concentration, emerging technologies, and potential opportunity domains and can therefore support research and innovation planning rather than merely cataloguing existing patents (Grant et al., 2014; Kortov et al., 2017; van Rijn & Timmis, 2023). The Continuous Innovation and Patent Intelligence loop shown beneath the six pathways reinforces this function by ensuring that newly generated knowledge, patent activity, emerging actors, and subsequent technological developments are continuously returned to the intelligence stage for reassessment.

Pathways 2 and 3: Core Thermal Technology Development and Integration for Preservation represent the transition from evidence to technological development. The CPC analysis demonstrates substantial concentration in classifications associated with body-temperature regulation and cooling, including A61F2007/126, A61F7/12, and A61F2007/0054, while A61P and A61K classifications indicate intersections with therapeutic, biological, and pharmaceutical applications. Thus, the second pathway, Core Thermal Technology Development, emphasizes advancing established cooling and thermal-management technologies, while the third pathway, Integration for Preservation, extends these technologies

toward integrated preservation systems involving cooling, physiological monitoring, biological stabilization, and related cryogenic processes. This interpretation is also consistent with the multidisciplinary character of the patent landscape, in which organizations associated with biomedical, pharmaceutical, circulatory-support, and cooling technologies appear among major applicants and owners. Patent landscaping can facilitate such technological convergence by revealing relationships among classifications, patent families, organizations, and technological domains (Grant et al., 2014; van Rijn & Timmis, 2023). In the TIPF, therefore, cooling is not conceptualized as an isolated intervention but as a technological component that can be progressively integrated into broader preservation architectures. This creates a transition from core thermal capability to preservation integration and ultimately to system-level technological development.

Pathway 4: Intelligent Rewarming and Recovery extends the framework beyond preservation toward the controlled restoration of physiological conditions, while Pathway 5: Validation and Translational Development provides the evidence and verification stage necessary before broader implementation. The aggregate patent findings demonstrate considerable activity around cooling and temperature control, but they do not by themselves establish an equally prominent integrated architecture connecting cooling, preservation, controlled rewarming, and recovery. Therefore, the figure appropriately presents intelligent rewarming and recovery as a proposed technological pathway, rather than as a confirmed technological absence. Potential development areas include controlled rewarming, continuous temperature monitoring, physiological feedback, adaptive thermal regulation, and recovery assessment, potentially leading to closed-loop systems in which thermal parameters are adjusted according to monitored physiological conditions. Such possibilities require claim-level patent examination and scientific, engineering, and biological validation before conclusions regarding technological novelty or feasibility can be made. The citation structure of the landscape can help identify influential technological foundations for this pathway: the dataset includes patents with approximately 710 and 550 forward citations, as well as several patents with approximately 100–300 citations. However, patent citations are influenced by patent age, citation practices, and other contextual factors; consequently, citation counts should be used as indicators for further investigation rather than as independent measures of technological importance (Aristodemou & Tietze, 2018; Mariani et al., 2019). Validation and Translational Development therefore connects technological concepts with engineering testing, biological or clinical validation where applicable, regulatory assessment, performance evaluation, and evidence generation. This pathway is supported by the principle that patent-landscape findings should inform, rather than substitute for, subsequent technical and scientific assessment (Grant et al., 2014; van Rijn & Timmis, 2023).

Pathway 6: IP, Technology Transfer, and Commercialization completes the principal sequence of the TIPF by translating validated technological outputs into intellectual-property strategies, technology transfer, licensing, partnerships, and potential commercialization, while the Cross-Cutting Enablers, interdisciplinary collaboration, funding and infrastructure, regulatory readiness, market validation, and global engagement support all six pathways. The landscape demonstrates considerable concentration among applicants and owners, while jurisdictional activity is strongly concentrated in the United States (approximately 74%), followed by WO–WIPO filings (approximately 21%) and Europe (approximately 5%). Such concentration provides an empirical basis for emphasizing broader collaboration and technology-transfer mechanisms, but it should not be interpreted automatically as evidence that other jurisdictions lack technological capability. Applicant, ownership, and geographic counts can be influenced by portfolio strategies, corporate structures, filing practices, funding environments, and jurisdictional preferences. Similarly, an apparent white space should be treated as an evidence-informed opportunity domain rather than a confirmed technological void, because low patent activity does not necessarily establish the absence of innovation, and patent inactivity or expiration does not by itself establish freedom to operate. The final feedback loop in the figure is therefore essential: technologies that undergo validation, IP development, transfer, and commercialization generate new knowledge and subsequent patent activity, which returns to Patent Intelligence for renewed analysis. In this sense, the TIPF functions as a continuous pathway connecting patent intelligence, core thermal development, preservation integration, intelligent rewarming and recovery, validation and translation, intellectual property, technology transfer and commercialization, and renewed patent intelligence, with cross-cutting enablers providing the organizational, financial, regulatory, scientific, and market conditions necessary to sustain the innovation cycle. This iterative interpretation is consistent with the use of patent landscapes as tools for monitoring technological evolution and informing research and innovation strategies (Kortov et al., 2017; van Rijn & Timmis, 2023).

CONCLUSIONS

This study demonstrates that the patent landscape for refrigeration, cooling, and cryogenic technologies for human-body preservation and recovery is active, multidisciplinary, and unevenly developed, with renewed patent activity after 2016, strong concentration in medical cooling and thermal-management technologies, and substantial activity among identifiable owners and inventors. The major innovation opportunity lies not simply in developing additional cooling technologies but in integrating thermal capabilities across the preservation-to-recovery continuum. The identified gaps in preservation–rewarming–recovery integration, advanced cryogenic preservation, intelligent closed-loop thermal management, preservation-oriented applications, and interdisciplinary collaboration are addressed through the proposed Technology Innovation Pathways Framework (TIPF). The framework provides a strategic pathway connecting patent intelligence, core thermal development, preservation integration, intelligent rewarming and recovery, validation and

translation, intellectual property, technology transfer, commercialization, and renewed patent intelligence. Its novelty lies in transforming fragmented patent evidence into an integrated innovation pathway that can guide research priorities, technology development, collaboration, and intellectual-property planning. The findings are applicable to researchers, engineers, universities, technology-transfer offices, innovators, and organizations seeking evidence-informed directions for future technology development. However, the study is limited by its reliance on the Lens database and defined Boolean search strategy, the possibility of incomplete recent patent records, classification and name-harmonization issues, and the inability of patent indicators alone to establish scientific feasibility, clinical effectiveness, commercial success, or freedom to operate. Future research should therefore pursue claim-level patent analysis, deeper technology-family and cluster analysis, scientific and engineering validation of identified white spaces, freedom-to-operate assessment, regulatory and market evaluation, and longitudinal monitoring, particularly for intelligent thermal control, cryogenic preservation, controlled rewarming, and integrated preservation-and-recovery systems.

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