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A Review: Global Patent Landscape and Technology Trends in Uranium Recovery from Seawater

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1. Introduction

Uranium recovery from seawater represents a promising pathway to secure the long-term sustainability of nuclear energy, as it enables access to an effectively inexhaustible resource compared to finite terrestrial reserves. Early research and development activities in this field—conducted primarily in Japan, the United States, and parts of Europe—were limited in both scale and continuity. In contrast, China has recently established a large-scale national consortium that integrates more than 30 national laboratories and universities, with the ambitious objective of achieving commercial deployment of seawater uranium extraction technologies by 2050.

Despite such progress, commercialization continues to face significant challenges, the most critical of which are economic. The feasibility of large-scale deployment is ultimately governed by the performance of adsorption materials, encompassing key parameters such as adsorption capacity, selectivity toward uranium over competing ions, adsorption and desorption kinetics, long-term durability, and resistance to marine biofouling [1]. These factors directly determine material efficiency, process scalability, and overall cost-effectiveness.

To better understand the current state of technological innovation, we conducted a systematic analysis of international patent filings and grants related to uranium recovery from seawater. Our study maps the technical subdomains represented in the patent landscape, while also examining temporal trends across major jurisdictions. Through this approach, we aim to identify not only the dominant contributors and emerging themes but also the trajectory of global efforts toward overcoming the remaining barriers to commercialization.

2. Methods

2.1. Search conditions and preliminary results

Patent searching was conducted using the WINTELIPS database to examine recent developments in uranium extraction from seawater, a field that has emerged recently. To ensure broad coverage, the following query was employed as follows:

(sea OR ocean OR marine) AND (uranium* OR uranyl*) in title, abstract, or claims***

A total of 1,213 raw patent documents were identified across major jurisdictions, including Korea, Japan, China, the United States, the European Patent Office, PCT applications, Canada, and Australia. Following removal of duplicates and exclusion of documents related to terrestrial uranium mining and unrelated environmental remediation, 305 patents were retained for detailed analysis.

The results reveal strong global activity in this field, particularly since 2020. China dominates the landscape with 266 patents (87% of the total), while Japan (15 patents) and the United States (12 patents) contribute modestly. Other jurisdictions show only marginal representation. This concentration of patent activity underscores China’s leadership in advancing seawater uranium recovery technologies.

2.2. Technology classification

For analytical purposes, the identified patents were categorized into four major process stages along the seawater uranium resource cycle.

Uranium Extraction: This stage focuses on adsorbing uranyl ions directly from seawater using specialized sorbent materials designed to achieve high capacity, selectivity, and durability under marine conditions.

Uranium Desorption: Once adsorbents are saturated, uranium must be efficiently released into an elution solution. This stage covers chemical and physical methods that regenerate adsorbents while maximizing recovery efficiency.

Purification and Separation: Extracted uranium is often accompanied by competing ions and impurities. Technologies in this stage are directed toward isolating uranium from mixed ion solutions to obtain higher purity and stability of the recovered product.

High-Purity Conversion: The final stage involves refining the purified uranium into high-purity forms, suitable for downstream nuclear fuel applications. Patents in this category address crystallization, precipitation, and other chemical conversion techniques.

Together, these four stages represent a comprehensive framework for mapping technological innovations across the seawater uranium recovery cycle, from initial adsorption in the marine environment to the production of nuclear-grade uranium.

The technology definition and following keywords are presented in Fig. 1.

중분류	소분류	기술정의	필수 키워드 (확장)
해수 우라늄	우라늄 추출(AA)	**해수 용존 우라닐 이온을 흡착**하여 **우라늄을 추출하는 소재** 및 소재가 수반 된 공정	해수(바닷물, 염수, seawater, marine, ocean)
	우라늄 탈착(AB)	우라닐 이온이 흡착된 소재로부터 **우라늄을 탈착하는 용액** 또는 용액이 수반된 공정	탈착(Desorption), 용리(Elution)
	정제 및 분리(AC)	우라늄과 경쟁이온이 용존 된 **혼합 수용액 또는 용매로부터 우라늄을 분리**하는 공정	용액(Solution), 분리(Separation)
	고순도화(AD)	자원으로 활용하기 용이하도록 **고순도 분말 등으로 가공**하는 기술	고순도화(Purification) 침전(Precipitation)

Fig. 1. Technology classification for searching patent related to uranium recovery from seawater

3. Results and discussion

3.1. Technology trend in adsorbent support development

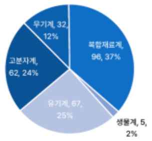
Among the 305 effective patents identified, 262 explicitly specify the type of adsorbent material employed. Within this set, composite materials account for the largest share with 96 cases (36.6%), followed by organic adsorbents (67 cases, 25.6%), polymer-based systems (62 cases, 23.7%), inorganic adsorbents (32 cases, 12.0%), and bio-based materials (5 cases, 2.0%). This distribution highlights the strong emphasis on hybrid designs that combine the structural advantages of polymers with the functional properties of inorganic additives.

From a technological perspective, adsorption dominates the landscape, appearing in 193 patents (73.7%), underscoring its role as the most mature and scalable approach for uranium recovery from seawater. Other methods are also represented, including membrane separation (25 cases), photocatalysis (27 cases), and electrochemical techniques (18 cases), reflecting ongoing exploration of alternative or complementary pathways.

Particularly noteworthy is the rise of polymer–inorganic composite adsorbents, which demonstrate improvements in both selectivity and capacity. These systems are increasingly recognized as promising candidates for bridging the gap between laboratory-scale performance and the requirements for practical, large-scale deployment.

When classified into five time periods (before 2000, 2000–2009, 2010–2014, 2015–2019, and post-2020), the patent landscape reveals a sharp increase in activity since 2020. This surge can be attributed both to the growing strategic importance of seawater uranium recovery technologies and to heightened environmental regulations that demand more efficient extraction processes.

In terms of material categories, composite systems exhibit the most pronounced growth, driven by advances in nanotechnology, integrated material design, and more recently, AI-assisted optimization of adsorbent structures. Organic and polymer-based adsorbents also show a steady upward trajectory, reflecting their continued relevance and adaptability. By contrast, inorganic materials have remained relatively stagnant, suggesting limitations in scalability or performance improvements. Bio-based adsorbents, though only emerging in recent years and representing a small fraction of the total, align with broader sustainability trends and may hold significant potential for future development.



구분	고분자계 (수지, 에어로겔, 섬유 등)	무기계 (제올라이트, 활성탄 등)	복합재료계	생물계	유기계 (COFs, MOFs 등)	총합계
광촉매	3	2	15	1	5	27
기타	4	1	3	4	3	42
멤브레인	11	3	8			25
전기화학	1	5	6			18
흡착	43	21	64		59	193
총합계	62	32	96	5	67	262

Fig. 2. Patent landscape on Adsorbent Support development

3.2. Patent landscape on performance verification in real seawater

Among the 305 effective patents identified, only 60 cases (approximately 20%) reported adsorption performance verified under actual seawater conditions. Among these, China accounts for 52 patents, underscoring its dominant role in advancing practical testing. In terms of functional groups, amidoxime (AO)-based ligands represent the largest share with 18 patents (30%), reflecting their continued prominence as the benchmark for seawater uranium adsorption.

Nevertheless, even in these field-tested cases, major challenges remain unresolved, particularly the effects of competing ions in seawater, the impact of biofouling, and long-term environmental degradation of adsorbents. These persistent issues highlight the critical gap between laboratory-scale performance and reliable large-scale deployment, emphasizing the need for next-generation materials and system-level solutions.

4. Conclusions

This patent landscape analysis shows that innovation in seawater uranium recovery has grown rapidly over the past two decades, with an especially sharp increase since 2020. China stands out both in volume and diversity of patents, reflecting a coordinated national strategy driven by large-scale research consortia. Among material types, polymer–inorganic composites have expanded most strongly, supported by progress in nanotechnology, hybrid material design, and even AI-driven optimization. Organic and polymer adsorbents have continued to advance at a steady pace, while inorganic systems appear to have plateaued. Bio-based adsorbents remain a small category, but their connection to sustainability trends suggests they may become increasingly important in the future.

At the same time, practical validation are still left behind. Only about 20% of patents report testing under real seawater conditions, with China again accounting for the majority. Amidoxime-based ligands remain the dominant chemistry, but persistent issues—such as interference from competing ions, biofouling, and long-term material degradation—still stand in the way of practical deployment. Closing this gap will require not only more durable, multifunctional adsorbent support, but also system-level engineering solutions that can translate laboratory success into reliable large-scale applications.

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[1] Chong Liu et al., A half-wave rectified alternating current electrochemical method for uranium extraction from seawater, Nature Energy, 2, 17007(2017)