

Water Scarcity as an Economic Barrier to Domestic USY Zeolite Production (Mini review)

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Article history

Received: 4 July 2025

Revised: 20 August 2025

Accepted: 1 September 2025

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Abstract: Owing to its inherent stability and characteristic structure, Ultra-Stable Y (USY) zeolite is indispensable as a key component in the Fluid Catalytic Cracking (FCC) catalysts. Developing indigenous synthesis capabilities for this valuable mineral would significantly strengthen the nation's catalyst and absorbent industries. Nonetheless, the pervasive water scarcity crisis in Iran poses a critical challenge for water-intensive industries, including zeolite manufacturing, necessitating diligent attention to water usage. In this regard, water consumption in industrial zeolite production is investigated in the current short-review article.

Keywords: Water Scarcity, Ultra-Stable Y zeolite, Fluid Catalytic Cracking

Introduction

Ultra-Stable Y (USY) zeolite is obtained from Na-Y zeolite through post-synthetic treatments, chiefly involving steaming and acid leaching. These modification processes raise the Si/Al ratio, thereby enhancing the zeolite's stability under the demanding conditions typical of fluid catalytic cracking (FCC) operations. Additionally, they generate mesopores, resulting in a hierarchical structure that facilitates improved access for reactants. Industrial-scale production typically begins with the synthesis of Na-Y from precursors such as sodium silicate and sodium aluminate (or alternative materials like kaolin), followed by these energy-intensive modification stages. USY zeolite exhibits a suite of key physicochemical properties that makes it highly valuable in various applications, particularly catalysis. These properties include high surface area, microporosity, strong acidity, and remarkable thermal and hydrothermal stability. Furthermore, its inherent ion-exchange capacity allows for additional functionalization and property tuning. The interconnected network of super cages and channels within the FAU framework offers extensive internal surface area for adsorption and catalytic reactions. Industrial applications of USY zeolite are listed in Table 1 [1, 2].

Despite its broad utility across the oil and gas, petrochemical, agricultural, and health sectors, zeolite production is a highly water-intensive process. This environmental burden is especially pronounced in the case of USY zeolite, whose synthesis and post-treatment demand exceptional water purity and volume. From hydrothermal crystallization of Na-Y to the repeated washing, ion exchange, and acid leaching steps, large volumes of high-pure water are required. On an industrial scale, the water that is needed for producing one ton of USY can reach several cubic meters. This poses a significant challenge in many countries experiencing water scarcity whether due to climate change, over-extraction, population growth, or industrial competition—especially in regions like the Middle East, North Africa, South Asia, and parts of Latin America [3, 4].

As the demand for zeolites continues to grow globally, water scarcity is emerging as a key constraint for sustainable production. Many developing economies face the dual challenge of industrial growth and limited water infrastructure, making the expansion of zeolite production economically and environmentally complex. Even in water-rich countries, increasing awareness of environmental responsibility and stricter regulations are pressuring manufacturers to reduce their water footprint. This evolving regulatory landscape is prompting a shift toward greener synthesis routes, including closed-loop

water systems and low-liquid-phase processing techniques, which aim to minimize environmental impact without compromising product quality [5]. These pressures may lead to higher costs, production bottlenecks, and barriers to localizing supply chains.

This study explores how global water stress influences the economics of USY zeolite production. It examines water-intensive stages of the manufacturing process, regional disparities in water access, and the potential for mitigation through recycling technologies, dry-process innovations, and international cooperation. Ultimately, it seeks to identify pathways for sustainable zeolite production that balance technological advancement with responsible resource management in both water-rich and water-stressed regions of the world [6–8].

Table 1. industrial applications of USY zeolite

Application	Products/Outcomes	Key Properties
Fluid Catalytic Cracking	Gasoline, Diesel, Light Olefins	Acidity, Pore Size, Stability
Hydrocracking	Middle Distillates, Reformulated Products	Acidity, Stability, Bifunctional nature
Isomerization	Isomers of hydrocarbons	Acidity, Pore Size
Alkylation	Alkylated hydrocarbons	Acidity, Pore Size
Organic Synthesis	Various organic compounds	Acidity, Pore Size, Modified sites
NO _x Reduction	Nitrogen (N ₂)	Acidity, Metal-modified sites
Biomass Conversion	Biofuels, Platform Chemicals	Acidity, Pore Size

General Procedure of USY Zeolite Production

The production of Ultra-Stable Y (USY) zeolite begins with some key raw materials including water, sodium hydroxide (NaOH), alumina trihydroxide (Al(OH)₃), sodium oxide (Na₂O), sodium silicate (Na₂SiO₃), sodium aluminate (NaAlO₂), sulfuric acid (H₂SO₄), and aluminum sulfate (Al₂(SO₄)₃). These components are carefully prepared and combined to form the precursor solutions necessary for zeolite crystallization. The

purity and stoichiometric balance of these reagents are critical to achieving consistent phase formation and optimal framework composition.

Initially, sodium aluminate and sodium silicate solutions are separately prepared and then mixed together to form a homogeneous seed mixture. This mixture undergoes an aging step under controlled conditions to promote the formation of nuclei essential for zeolite crystallization. Subsequently, the seed mixture is combined with fresh sodium aluminate, sodium silicate, a recycled silica-alumina hydrogel stream, and sulfuric acid in crystallization reactors maintained at approximately 100 °C. Under these hydrothermal conditions, crystalline Na-Y zeolite forms over a controlled reaction period. Precise control of temperature, pH, and aging time during this stage is essential to ensure the formation of the FAU-type framework with desired particle morphology and crystallinity [9].

Once crystallization is complete, the solid Na-Y zeolite is separated from the mother liquor by filtration and thoroughly washed with hot water to remove impurities. The washed crystals are then sent to storage for further processing. The residual crystallization mother liquor is processed to recover silica and alumina in the form of a silica-rich hydrogel, which is recycled back into the production cycle, improving raw material efficiency. This recycling step not only enhances sustainability but also reduces the overall cost of production by minimizing waste and conserving valuable feedstocks.

To convert the Na-Y zeolite into Ultra-Stable Y (USY) zeolite, a multi-step post-synthesis modification procedure is applied. The present process primarily involves repeated ammonium ion exchange steps, typically using an aqueous ammonium sulfate ((NH₄)₂SO₄) solution. After each ion exchange, the material is filtered, dried, and subjected to calcination (thermal treatment) to decompose the ammonium ions and stabilize the framework. Several cycles of exchange and calcination are carried out, including a high-temperature steam calcination step designed to partially remove aluminum from the zeolite framework—a process known as dealumination. This dealumination improves the silica-to-alumina ratio and enhances the thermal and hydrothermal stability of the zeolite.

During these ion exchange and calcination cycles, extra-framework aluminum species generated by dealumination are progressively removed, ensuring that the final product has minimal sodium content and a stable, optimized framework structure. The removal of sodium and extra-framework aluminum is crucial for achieving high acidity and catalytic performance,

particularly in FCC applications where thermal resilience and pore accessibility are paramount. The resulting USY zeolite is characterized by a high silica-to-alumina (Si/Al) ratio typically ranging between 25 and 35, and a large specific surface area in the range of 700 to 800 m²/g. These properties make USY zeolite particularly suitable for demanding catalytic applications such as fluid catalytic cracking (FCC) in the petroleum refining industry [10–12].

In industrial practice, the reproducibility of USY properties is ensured through rigorous quality control protocols, including X-ray diffraction (XRD), nitrogen adsorption-desorption analysis (BET), and scanning electron microscopy (SEM), which confirm phase purity, surface area, and particle morphology. Additionally, thermal gravimetric analysis (TGA) and ammonia temperature-programmed desorption (NH₃-TPD) are employed to assess thermal stability and acidity profiles, respectively, which are critical for catalytic performance benchmarking [13].

Water Requirements in USY Zeolite Production Steps

The production of Ultra-Stable Y (USY) zeolite is a complex process that involves multiple stages, each with significant water requirements. Water plays a critical role from the very beginning, starting with the preparation and purification of raw materials such as silica and alumina. These materials often require dilution, dissolution, and cleaning steps that depend heavily on water to ensure the quality and consistency necessary for successful zeolite synthesis. In industrial settings, the water used in these initial steps must meet stringent purity standards to avoid contamination of the crystallization process and ensure reproducibility of product quality.

During the hydrothermal synthesis stage, where the initial Na-Y zeolite crystals form, water serves as both a solvent and a medium for chemical reactions. This step takes place under carefully controlled temperature and pressure conditions, typically around 100 °C, in an alkaline aqueous solution. Because the synthesis involves large volumes of liquid to maintain proper reaction conditions and to allow crystal growth, it represents one of the most water-intensive phases of USY production. The ratio of liquid to solid in this stage is deliberately kept high to promote uniform nucleation and crystal development, which directly influences the final zeolite morphology and porosity [9].

Following crystallization, the zeolite undergoes ion exchange to convert Na-Y into the ultra-stable USY

form. This stage involves repeatedly exchanging sodium ions with ammonium ions in aqueous ammonium sulfate solutions. Each ion exchange cycle requires substantial amounts of water not only to prepare the exchange solutions but also for thorough washing between cycles to remove excess ions and impurities. The efficiency of ion exchange and the completeness of washing directly affect the acidity and catalytic performance of the final USY product, making water quality and volume critical parameters in this stage.

In addition to ion exchange, extensive washing and filtration steps are also necessary throughout the entire production process. These washing steps are crucial for removing by-products, residual chemicals, and soluble salts that accumulate during synthesis and modification. Although filtration efficiently separates solids from liquids, the washing stages significantly add to overall water consumption, as multiple rinses are often required to achieve the desired purity. In practice, each washing cycle may consume several cubic meters of water per ton of zeolite, depending on the scale and configuration of the production line.

The post-synthesis modification steps, which include high-temperature steaming and acid leaching to dealuminate the zeolite framework, also contribute notably to water usage. Steaming requires controlled humid conditions, often generated by injecting steam, while acid leaching involves aqueous acid solutions. Both processes are critical for enhancing the thermal stability and catalytic performance of USY zeolite but come at the cost of increased water demand. Moreover, the acid leaching step generates wastewater streams containing dissolved aluminum and sulfate species, which require careful treatment before discharge or reuse, further complicating water management [13].

Finally, the drying stage removes moisture from the zeolite crystals; although this step reduces water content, it is preceded by the removal of large amounts of water in the earlier stages. Overall, the cumulative water consumption in USY zeolite production is significant, posing challenges for sustainable manufacturing, especially in regions facing water scarcity. A detailed summary of water use across these stages is illustrated in Figure 1 [14–15].

Based on research in USY zeolite production, particularly for FCC catalyst manufacturing, the formulations have been successfully developed at laboratory and pilot scales, demonstrating potential for industrial scale-up. However, economic feasibility studies reveal that the substantial water consumption inherent to the USY production process presents a significant barrier, especially in the context of increasing water scarcity and the critical demand for water resources. Consequently, domestic production under current conditions is not considered cost-

effective. This is largely because efforts to reduce water usage with existing state-of-the-art technologies tend to negatively impact the quality of the final zeolite product. For example, attempts to shorten washing cycles or reduce liquid-phase volumes often result in incomplete ion exchange or residual impurities, which degrade catalytic performance and reduce product lifespan [15].

Therefore, achieving economically viable production of high-quality USY zeolite amid prevailing water limitations remains a formidable challenge. To overcome this challenge, several strategies can be considered:

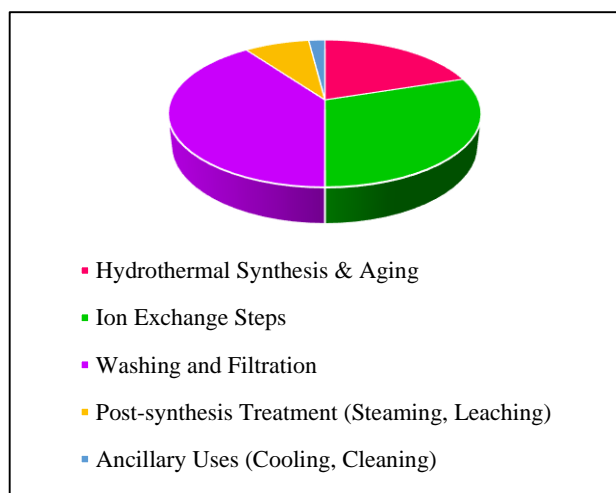


Fig. 1. Graphical of water consumption in various stages through USY production approximately.

Water Recycling and Reuse

Water recycling involves capturing wastewater generated during the USY zeolite production process, treating it to remove impurities, and reusing it within the plant. This reduces the demand for fresh water and lowers wastewater discharge, thus mitigating environmental impacts. Given the high-water footprint of USY synthesis—particularly during crystallization, ion exchange, and post-treatment stages—integrating water recycling systems is increasingly recognized as a strategic imperative for sustainable manufacturing.

Advanced treatment technologies such as membrane filtration (microfiltration, ultrafiltration), reverse osmosis, and advanced oxidation processes enable high-quality water recovery suitable for sensitive synthesis and washing steps. These technologies are capable of removing suspended solids, dissolved salts, organic contaminants, and trace metals, thereby

producing recycled water that almost meets the stringent purity requirements of zeolite production. Reverse osmosis, in particular, offers high rejection rates for ionic species and is widely adopted in chemical industries for reclaiming process water. Advanced oxidation processes (AOPs), including ozonation and photocatalysis, are effective in degrading persistent organic compounds that may interfere with zeolite crystallization or catalytic performance [16–17].

Implementing closed-loop water systems not only conserves water but also reduces operational costs by decreasing the volume of water purchased and wastewater treated. Such systems are designed to continuously recycle internal water streams, minimizing external intake and discharge while maintaining process integrity. Beside economic benefits, closed-loop configurations contribute to regulatory compliance, especially in regions with strict effluent discharge limits or water abstraction quotas.

However, the successful deployment of water recycling infrastructure in zeolite plants requires careful engineering to prevent contamination buildup, scaling, and microbial growth. Over multiple cycles, recycled water may accumulate trace impurities or undergo chemical changes that affect its suitability for reuse. Therefore, robust monitoring protocols and adaptive treatment strategies must be integrated to ensure consistent water quality. Inline sensors, automated dosing systems, and predictive maintenance models are increasingly used to optimize recycling performance and prevent process disruptions [18].

Moreover, the compatibility of recycled water with each production stage must be validated through pilot-scale trials and quality assurance testing. For example, recycled water used in ion exchange must not contain residual cations that could interfere with ammonium exchange efficiency. Similarly, water used in acid leaching must be free of buffering agents or organic residues that could neutralize acid strength or alter dealumination kinetics.

In summary, water recycling and reuse represent a viable pathway toward reducing the environmental and economic burden of USY zeolite production. While initial capital investment and system complexity may pose challenges, the long-term benefits in terms of resource conservation, cost reduction, and regulatory alignment make water recycling a cornerstone of sustainable catalyst manufacturing.

Process Intensification

Process intensification refers to modifying and

optimizing reaction conditions to achieve the same or better results with reduced inputs, including water. In USY zeolite synthesis, this may involve reducing reaction times, operating at lower temperatures or pressures, or using more concentrated reactants to minimize water volumes. The overarching goal is to enhance the process efficiency, reduce resource consumption, and minimize environmental impact without compromising product quality or performance. Techniques such as microwave-assisted synthesis and ultrasonication can accelerate crystallization and ion-exchange steps, lowering water consumption and energy use. Microwave irradiation promotes rapid and uniform heating, which enhances nucleation rates and shortens crystallization time, while ultrasonication improves mass transfer and dispersion of reactants, facilitating more efficient ion exchange and dealumination. These methods have demonstrated promising results in laboratory-scale studies, showing potential for scale-up in industrial applications [19–20].

Additionally, shifting from batch to continuous flow reactors can improve control and efficiency. Continuous flow systems offer superior control over reaction parameters such as temperature, residence time, and reagent concentration, enabling consistent product quality and reduced variability. They also allow for real-time monitoring and adjustment, which is particularly advantageous in multi-step processes like USY synthesis that involve sequential crystallization, ion exchange, and thermal treatment. Moreover, continuous reactors can be integrated with inline purification and recycling modules, further enhancing water and energy efficiency [21].

Other emerging strategies include high-solid-content synthesis, where reactant concentrations are increased to reduce solvent volume, and reactive extrusion, which combines mixing, heating, and shaping in a single step. These approaches are being explored to reduce water usage and simplify process logistics, though their compatibility with the delicate FAU-type framework of USY zeolite requires further validation. However, any change must ensure that the hierarchical pore structure, acidity, and thermal stability of USY zeolite are maintained to preserve catalytic performance. The integrity of the microporous and mesoporous architecture, the strength and distribution of acid sites, and the framework stability under FCC conditions are non-negotiable parameters that must be preserved during process optimization. Therefore, process intensification must be guided by rigorous characterization and performance benchmarking to ensure that gains in efficiency do not compromise functional properties.

In summary, process intensification offers a promising pathway to reduce water and energy demands in USY zeolite production. Its successful implementation depends on balancing innovation with structural fidelity, ensuring that the modified synthesis routes yield zeolites with comparable or superior catalytic behavior to those produced via conventional methods.

Alternative Synthesis Methods

Traditional hydrothermal synthesis of USY zeolite is water-intensive. Alternative methods seek to reduce water usage by employing minimal solvent volumes or solvent-free approaches. These emerging strategies aim to decouple zeolite crystallization from conventional aqueous media, thereby addressing the environmental and economic constraints associated with high water consumption.

Mechanochemical synthesis uses mechanical energy (e.g., ball milling) to induce zeolite formation without or with little water. This solvent-free or low-solvent technique relies on solid-state reactions driven by mechanical activation, which facilitates bond breakage and reformation at ambient or mildly elevated temperatures. Mechanochemical routes have demonstrated the ability to produce zeolitic phases with acceptable crystallinity and porosity, although the control over framework topology and particle size distribution remains a key area of ongoing research [22].

Another approach is the use of minimal hydrothermal media, often combined with ionic liquids or deep eutectic solvents, which can enhance crystallization efficiency and reduce water footprint. Ionic liquids, due to their tunable polarity and thermal stability, can serve as alternative reaction media that promote selective nucleation and growth of zeolite crystals. Deep eutectic solvents, formed by mixing hydrogen bond donors and acceptors, offer similar advantages with lower toxicity and cost. These solvents can facilitate the dissolution of silica and alumina precursors, improve mass transfer, and enable controlled crystallization under milder conditions [23–24].

In addition to reducing water usage, these alternative media may allow for lower synthesis temperatures, shorter reaction times, and improved incorporation of heteroatoms or functional groups into the zeolite framework. However, their compatibility with large-scale production remains limited by factors such as solvent recovery, cost of reagents, and variability in product quality. The physicochemical properties of USY zeolite—particularly its hierarchical pore structure, acidity profile, and thermal stability—must

be rigorously validated when synthesized via non-traditional routes to ensure suitability for catalytic applications.

Furthermore, the environmental impact of these alternative solvents must be assessed holistically, considering factors such as biodegradability, recyclability, and potential toxicity. Life cycle analysis and techno-economic evaluation are essential to determine whether these methods offer a net sustainability benefit over conventional hydrothermal synthesis.

Integration of Renewable Energy

The production of USY zeolite involves energy-intensive steps, especially in water treatment and high-temperature steaming or calcination. Utilizing renewable energy sources such as solar thermal, wind, or biomass-derived power can reduce carbon footprint and make water treatment processes more sustainable. As global pressure mounts to decarbonize industrial operations, integrating clean energy into zeolite manufacturing is becoming a strategic priority for both environmental compliance and long-term economic viability.

For example, solar-driven evaporation or advanced oxidation processes can treat and recycle water on-site using clean energy. Solar thermal systems can be employed to generate steam for dealumination and drying steps, while photovoltaic-powered oxidation units can drive photocatalytic degradation of organic contaminants in wastewater streams. These applications not only reduce fossil fuel dependency but also enable decentralized water treatment in regions with limited infrastructure [24–25].

Additionally, electrification of synthesis reactors powered by renewable electricity can reduce reliance on fossil fuels. Electrically heated reactors offer precise temperature control and rapid response times, which are advantageous for crystallization and calcination processes. When coupled with renewable electricity—such as solar PV or wind-generated power—these systems can significantly lower greenhouse gas emissions associated with thermal processing. Recent advances in modular reactor design and smart grid integration have made it feasible to operate energy-intensive units like steam generators and calcination kilns using intermittent renewable sources without compromising process stability [26]. Biomass-derived energy, including biogas and pyrolysis heat, also presents a viable option for supplying thermal energy to zeolite plants, particularly in agricultural or rural settings where organic waste is

abundant. These systems can be configured to co-generate heat and power, supporting both water treatment and synthesis operations while contributing to circular economy goals.

To maximize the benefits of renewable integration, energy management systems must be implemented to synchronize energy supply with process demand. This includes load balancing, thermal storage, and predictive control algorithms that optimize energy use across production stages. Hybrid systems combining multiple renewable sources—such as solar and biomass—can offer greater reliability and flexibility, especially in regions with variable climate conditions. Combining renewable energy with efficient water management can enhance the overall sustainability of zeolite production. This dual approach not only reduces environmental impact but also strengthens resilience against resource scarcity and energy price volatility, positioning USY zeolite manufacturing as a model for green chemical processing [27–28].

Conclusion

The production of Ultra-Stable Y (USY) zeolite is a critical process for industrial applications, particularly in fluid catalytic cracking, but its high-water consumption presents a significant economic and environmental challenge, especially in regions facing water scarcity. Addressing this issue requires a multifaceted approach that balances maintaining product quality with sustainable resource use. Implementing closed-loop water recycling systems can significantly reduce freshwater demand while advanced process intensification methods offer pathways to minimize water usage without compromising the zeolite's performance. Moreover, exploring alternative synthesis techniques, such as mechanochemical and solvent-minimized methods, holds promise for drastically lowering water requirements. Finally, integrating renewable energy sources into the production and water treatment processes can further enhance environmental sustainability by reducing carbon emissions and reliance on nonrenewable resources. Combining these strategies paves the way for economically viable and environmentally responsible production of high-quality USY zeolite, essential for meeting industrial demands while conserving vital water resources. Current advanced production method requires substantial amount of water to maintain zeolite quality. Under water-scarce condition, achieving economically viable production of high-quality zeolite is not feasible.

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