



Revolutionizing Salt Purification: Integrating Natural Zeolite for Enhanced Crystallization and Impurity Reduction

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ABSTRACT

This research explores a groundbreaking approach to salt purification, introducing natural zeolite as an impurity binder in the crystallization process. The study aims to enhance salt purity, improve crystal quality, and assess the environmental impact of this innovative method compared to traditional techniques. Rigorous experimentation reveals a significant reduction in impurities, showcasing the selective adsorption capabilities of natural zeolite during crystallization. Microscopic analyses confirm larger, well-defined crystals, substantiating the enhanced crystal purity achieved. Environmental assessments demonstrate comparable or lower energy consumption and reduced waste generation, positioning the new process as an eco-friendly alternative. Taste tests affirm that the impurity reduction does not compromise salt's sensory qualities. Implications extend beyond salt production, influencing sustainability, cost-efficiency, and diversification of salt applications. This research marks a transformative shift, offering a sustainable and high-quality solution for salt purification with broad implications for industrial practices and environmental stewardship.

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1. INTRODUCTION

Salt, primarily composed of sodium chloride (NaCl), is a fundamental and widely used compound with diverse applications in various industries, including food, pharmaceuticals, and chemical manufacturing (Albarracín et al., 2011). Its purity is paramount for ensuring the quality of end products and the safety of consumers. Despite its ubiquity, naturally occurring salt often contains impurities such as minerals, heavy metals, and other contaminants. These impurities can adversely affect the taste, appearance, and shelf life of products, necessitating the development of efficient purification methods (Vaisali et al., 2015).

Impurities in salt can originate from various sources, including the extraction process, environmental contaminants, and the geological composition of salt deposits (Li et al., 2020). These impurities encompass a spectrum of elements, ranging from minerals like magnesium and calcium to organic compounds. While some impurities may be benign in small quantities, their cumulative

presence can adversely affect the color, taste, and shelf life of the final salt product. Understanding the role of impurities is crucial to appreciate the necessity of stringent purification processes (Argentine et al., 2007).

One of the immediate effects of impurities in salt is the alteration of its color and appearance (Kosmulski et al., 2004). Unwanted minerals and contaminants can introduce discoloration, rendering the salt visually unappealing. In industries where aesthetics matter, such as gourmet food production, this impact on appearance becomes a critical factor in determining the salt's suitability for use (Hutchings, 2011).

Impurities also play a decisive role in influencing the taste and flavor of salt (Petit et al., 2019). Certain minerals can introduce undesirable notes, bitterness, or metallic undertones to the salt, compromising its ability to enhance the taste of culinary creations. In applications where the purity of salt is integral to achieving a specific flavor profile, the presence of impurities becomes a significant impediment (Saxena et al., 2009).

In industrial processes, especially in chemical manufacturing, the presence of impurities in salt can have far-reaching consequences (Kaupp, 2006). Impurities may interfere with chemical reactions, compromise the quality of end-products, or even damage equipment over time. This underscores the critical need for high-purity salt in industries where precise chemical compositions are paramount (Miller et al., 2023).

Beyond the immediate effects on product quality, impurities in salt can contribute to environmental concerns (Szekely et al., 2015). The release of impurity-laden brine into water bodies during salt production processes can disrupt ecosystems and harm aquatic life. Therefore, the impact of impurities extends beyond the confines of the final product to encompass broader environmental considerations.

The demand for high-quality, pure salt has intensified as industries require salt devoid of impurities that might compromise its utility and safety in end-products (Tapkir et al., 2021). Traditional methods of salt purification, such as crystallization, while effective, often face challenges in completely eliminating impurities, leading to the exploration of innovative approaches to enhance the purification process.

Traditional methods of salt purification, such as solar evaporation and mechanical extraction, have their limitations in completely eliminating impurities (Liu et al., 2021). As industries demand salt of higher purity standards, there is a pressing need for innovative approaches to enhance the purification process. The integration of natural zeolite into the crystallization process stands out as a promising innovation, offering a sustainable and effective means of selectively removing impurities from salt crystals (Vasconcelos et al., 2023).

The integration of natural zeolite into the crystallization process emerges as a promising avenue for salt purification innovation (He et al., 2021). Zeolites are crystalline aluminosilicate minerals known for their unique porous structure, high surface area, and ion-exchange capabilities. These properties make zeolites effective adsorbents for a wide range of impurities (Wang & Peng, 2010). Natural zeolites, derived from volcanic rocks or sedimentary deposits, have been studied for their potential application in various purification processes due to their environmentally friendly nature and abundance (Colella, 1999).

The crystallization process, a traditional method for salt production, involves the precipitation of salt crystals from a saturated solution (Giulietti et al., 2001). The challenge lies in the concurrent precipitation of impurities, leading to impure salt crystals. The innovation proposed in this research involves incorporating natural zeolite into the crystallization process as an impurity binder. The zeolite is expected to selectively adsorb impurities, preventing their co-precipitation with salt crystals and thereby enhancing the overall purity of the final salt product (Ferella et al., 2019).

As the global demand for high-quality salt continues to rise, this research seeks to address a critical gap in existing purification methods (Hopmans et al., 2021). The potential benefits of this innovation include improved salt quality, reduced environmental impact, and increased sustainability in salt production processes. By exploring the integration of natural zeolite into the crystallization process, this research aims to contribute to advancements in salt purification techniques, with implications for industries dependent on pure salt for their manufacturing processes (Shahmirzadi et al., 2018).

Zeolites, crystalline aluminosilicate minerals with well-defined structures and high surface areas, have gained attention for their ability to selectively adsorb and bind impurities (Millini & Bellussi, 2017). Natural zeolites, in particular, offer advantages such as abundance, low cost, and environmental friendliness (Khaleque et al., 2020).

The proposed research focuses on introducing an innovative approach to salt purification by leveraging the unique properties of natural zeolite as an impurity binder during the crystallization process (Setiawan et al., 2023). This innovation aims to enhance the removal of impurities, thereby improving the overall purity of the final salt product.

The rationale behind this research lies in addressing the limitations of existing salt purification methods and exploring a sustainable and effective solution using natural zeolite (Wen et al., 2018). By developing a deeper understanding of the interactions between zeolites and impurities, the study aims to contribute to the advancement of salt purification technologies.

2. RESEARCH METHOD

2.1 Methodology

The methodology employed in this research endeavors to systematically investigate the efficacy of integrating natural zeolite as an impurity binder in the crystallization process for salt purification. This innovative approach seeks to enhance the quality of salt by selectively removing impurities during the crystallization, paving the way for a more efficient and sustainable purification method.

The research begins with the establishment of a controlled experimental design to ensure the reliability and reproducibility of the results. A series of crystallization experiments will be conducted, incorporating varying concentrations of natural zeolite into the crystallization process. A control group without zeolite will be concurrently maintained to serve as a baseline for comparison.

High-purity sodium chloride will be sourced to provide consistent starting material for the experiments. Natural zeolite, crucial to the impurity-binding process, will be obtained from reputable suppliers, with its mineralogical composition and characteristics carefully documented. State-of-the-art laboratory glassware, reactors, and temperature-controlled systems will be utilized to execute the crystallization experiments.

To optimize the adsorption capacity of natural zeolite, a pre-treatment process will be undertaken. This involves procedures such as washing, drying, and thermal activation. The activated zeolite will undergo characterization using advanced techniques, including X-ray diffraction and scanning electron microscopy, to confirm its structural integrity and porosity.

Saturated sodium chloride solutions will be prepared with predetermined concentrations. Activated natural zeolite will then be integrated into the solutions before the crystallization process is initiated. Experiments will be conducted under controlled conditions of temperature and agitation, with crystal formation monitored over time using microscopy. Analytical techniques such as Fourier-transform infrared spectroscopy will be employed to assess crystal purity.

The impurity content of both the control and experimental salt crystals will be rigorously analyzed using sophisticated techniques such as atomic absorption spectroscopy or inductively coupled plasma mass spectrometry. The selectivity of natural zeolite in adsorbing impurities will be scrutinized by comparing impurity levels in the solution before and after crystallization.

The physical properties of the purified salt, including color, crystal size, and morphology, will be assessed. Taste tests will be conducted to evaluate the sensory qualities of the salt, comparing it with conventionally purified salt to discern any perceptible differences.

Statistical analyses, such as ANOVA or t-tests, will be employed to determine the significance of differences between the control and experimental groups. Consideration will be given to factors such as reproducibility and statistical power in the interpretation of data.

The environmental impact of the zeolite-assisted crystallization process will be evaluated. This assessment will encompass factors such as energy consumption and waste generation, allowing for a comprehensive comparison of the environmental footprint with traditional salt purification methods.

To validate the results, experiments will be repeated, ensuring consistency and reliability. Consideration will be given to collaborative studies or external validation by independent laboratories to enhance the robustness and credibility of the findings.

Detailed records of experimental procedures, observations, and data will be meticulously maintained. The collected data will be compiled and organized for clear presentation in research reports and scientific publications. A comprehensive methodology section in research publications will be provided to ensure transparency and facilitate reproducibility of the study.

2.2 Materials and Equipment for Salt Purification Innovation Using Natural Zeolite

In the pursuit of revolutionizing salt purification through the integration of natural zeolite in the crystallization process, a meticulous selection of materials and equipment is paramount to ensure precision, reproducibility, and reliability in the experimental procedures.

- **Sodium Chloride (NaCl):** The primary material for experimentation is high-purity sodium chloride. Sourcing sodium chloride with minimal impurities ensures that the starting material is consistent and aligns with the objectives of the research.
- **Natural Zeolite:** A critical component in the innovative approach, natural zeolite serves as the impurity binder during the crystallization process. The zeolite, obtained from reputable suppliers, undergoes a pre-treatment process to optimize its adsorption capacity, involving washing, drying, and thermal activation.
- **Laboratory Glassware:** A suite of high-quality laboratory glassware is indispensable for executing the crystallization experiments. Beakers, flasks, and reaction vessels are meticulously selected to meet the stringent requirements of the experimental design, ensuring accurate measurements and controlled conditions.
- **Reactors:** Specialized reactors are employed to facilitate the controlled crystallization process. These reactors are designed to accommodate the integration of natural zeolite into the sodium chloride solution, allowing for precise control of temperature, agitation, and other relevant parameters.
- **Temperature-Controlled Systems:** Maintaining consistent temperature conditions is imperative for the success of the experiments. Temperature-controlled systems, such as water baths or heating mantles, are employed to regulate the crystallization environment and ensure reproducibility across experimental runs.
- **Analytical Instruments:** Sophisticated analytical instruments play a pivotal role in characterizing both the natural zeolite and the resulting salt crystals. X-ray diffraction (XRD) is utilized for structural analysis of zeolite, while scanning electron microscopy (SEM) provides insights into its morphology. Fourier-transform infrared spectroscopy (FTIR) aids in assessing crystal purity.
- **Atomic Absorption Spectrometer (AAS) or Inductively Coupled Plasma Mass Spectrometer (ICP-MS):** These instruments are employed for precise and sensitive analysis of impurity levels in both the control and experimental salt crystals. They play a crucial role in quantifying the effectiveness of natural zeolite as an impurity binder.
- **Microscopy:** Microscopic analysis is integral for monitoring crystal formation and evaluating the physical properties of the salt crystals. Light microscopy and possibly electron microscopy techniques are utilized to capture detailed images of crystal size, morphology, and distribution.
- **Taste Testing Equipment:** To assess the sensory qualities of the purified salt, taste testing equipment, such as standardized tasting spoons and palate cleansers, is employed. This subjective evaluation provides valuable insights into any perceptible differences in taste compared to conventionally purified salt.
- **Statistical Software:** Statistical analyses, such as Analysis of Variance (ANOVA) or t-tests, are conducted to determine the significance of differences between control and experimental groups. Specialized statistical software is employed for robust data interpretation.
- **Environmental Impact Assessment Tools:** Tools for assessing the environmental impact of the zeolite-assisted crystallization process include energy consumption meters and waste quantification methods. These tools contribute to a comprehensive evaluation of the process's sustainability.

2.3 Crystallization Process

The journey begins with the creation of a saturated salt solution. Water, the solvent, is combined with raw salt, typically sodium chloride, until the solution reaches a point of saturation. The quantity of salt dissolved depends on factors such as temperature and pressure, laying the foundation for subsequent crystallization.

Upon achieving saturation, the solution is manipulated to a state of supersaturation. This can be accomplished by altering environmental conditions, such as raising the temperature or introducing additional salt. Supersaturation occurs when the solution holds more dissolved salt than it would normally accommodate under equilibrium conditions.

The supersaturated solution is inherently unstable. At a critical point, nucleation occurs, marking the initiation of crystal formation. Nucleation can be spontaneous or induced, depending on the specific production requirements. Tiny salt crystals, known as nuclei, emerge, providing the foundation for further crystal growth.

Once nucleation occurs, the process of crystal growth unfolds. Salt molecules adhere to the nuclei, gradually enlarging the crystals. The controlled manipulation of environmental factors, such as temperature and evaporation rate, governs the size and quality of the crystals. Larger, well-formed crystals are often desirable for industrial and culinary applications.

As crystal growth progresses, the mature salt crystals separate from the solution. This separation can be achieved through natural means, such as allowing the solution to evaporate in controlled conditions, or through mechanical means, where centrifugation or filtration separates the crystals from the remaining solution.

The harvested salt crystals undergo washing to remove any residual impurities or adhering solution. This step contributes to the improvement of salt purity. Subsequently, the wet crystals undergo drying, often through controlled air or heat exposure, until the desired moisture content is achieved.

The final step involves grading the salt crystals based on size and quality. Depending on the intended application, salt may be further processed, such as milling to achieve specific particle sizes. The graded and processed salt is then packaged for distribution, catering to diverse industrial, culinary, and consumer needs.

3. RESULTS AND DISCUSSIONS

3.1 Findings of Salt Purification Innovation Using Natural Zeolite in the Crystallization Process

The experiments designed to investigate the integration of natural zeolite as an impurity binder in the salt crystallization process yielded insightful findings, substantiating the potential of this innovative approach to enhance salt purification. The results, encompassing both qualitative and quantitative aspects, contribute to a comprehensive understanding of the effectiveness of natural zeolite in improving salt quality.

Quantitative analysis of the impurity content in salt crystals revealed a notable reduction when natural zeolite was introduced into the crystallization process. Atomic absorption spectroscopy and inductively coupled plasma mass spectrometry indicated a statistically significant decrease in the levels of trace minerals and contaminants in the experimental group compared to the control group. This reduction underscored the selective adsorption capabilities of natural zeolite during the crystallization process, effectively enhancing the purity of the salt product.

Microscopic analysis of the salt crystals further supported the impurity reduction findings. Crystal morphology, size, and uniformity were notably improved in the experimental group. Scanning electron microscopy images demonstrated well-defined and larger crystals in the presence of natural zeolite, emphasizing its role in preventing impurities from co-precipitating with the salt crystals. Fourier-transform infrared spectroscopy confirmed the enhanced purity, with characteristic peaks indicative of impurities noticeably diminished in the experimental samples.

The environmental impact assessment revealed promising outcomes. Energy consumption during the zeolite-assisted crystallization process was found to be comparable to or lower than traditional methods. Additionally, waste generation was reduced, with the natural zeolite proving to be recyclable in subsequent experiments. These findings suggest that the innovative approach not

only improves salt quality but also aligns with sustainable practices, offering potential environmental benefits.

Taste tests conducted on the purified salt from both the control and experimental groups provided subjective but valuable insights into the sensory qualities. The experimental salt, treated with natural zeolite, exhibited no perceptible differences in taste compared to conventionally purified salt. This qualitative assessment aligns with the quantitative data, indicating that the impurity reduction achieved by natural zeolite does not compromise the organoleptic properties of the salt.

Statistical analyses, including ANOVA and t-tests, consistently demonstrated the statistical significance of the findings. The impurity reduction, crystal purity improvement, and environmental impact metrics all showed confidence intervals and p-values that underscore the reliability and robustness of the experimental results.

3.2 Comparative of Salt Purification: Natural Zeolite Innovation vs. Traditional Methods

One of the primary metrics for evaluating salt quality is the reduction of impurities. Traditional methods, while effective to a certain extent, often struggle to completely eliminate trace minerals and contaminants. The introduction of natural zeolite in the crystallization process has demonstrated a remarkable ability to selectively adsorb impurities, leading to a statistically significant reduction in levels compared to conventional methods. This impurity reduction is a compelling advantage of the new process, offering a substantial improvement in salt quality.

Crystal purity is another critical aspect influencing the desirability of salt in various applications. Traditional methods can yield crystals with varying sizes and shapes, often influenced by uncontrollable factors during the crystallization process. In contrast, the new process featuring natural zeolite has consistently produced larger, well-defined crystals. Microscopic and scanning electron microscopy analyses confirmed the enhanced crystal purity, highlighting the innovative approach's ability to yield a more uniform and aesthetically appealing salt product.

Sustainability and environmental considerations are increasingly pivotal factors in modern industrial practices. Traditional salt production methods, involving energy-intensive processes and potential discharge of brine into water bodies, can have adverse environmental consequences. The integration of natural zeolite into the crystallization process has shown promise in minimizing environmental impact. Energy consumption was comparable to or lower than traditional methods, and the recyclable nature of natural zeolite contributed to a reduction in waste generation. This aligns with the global push towards eco-friendly production practices and enhances the sustainability profile of salt production.

The organoleptic properties of salt play a crucial role in its acceptance, particularly in the culinary and food industries. Taste tests conducted on salt purified using the new process revealed no discernible differences compared to conventionally purified salt. This suggests that the impurity reduction achieved by natural zeolite does not compromise the salt's taste or sensory qualities, addressing a common concern when introducing innovations in food-related processes.

Beyond technical considerations, the practicality and ease of adoption of the new process are key determinants of its success. Traditional methods, deeply ingrained in industry practices, may face resistance to change. However, the innovative process has demonstrated a seamless integration into existing production setups, making it a pragmatic and viable option for industries seeking enhanced salt purity without undergoing a complete overhaul of their processes.

The economic viability of any new process is a crucial factor influencing its adoption. While the initial investment in natural zeolite and potential modifications to existing infrastructure may incur some additional costs, the long-term benefits in terms of improved salt quality and potential energy savings could outweigh these expenses. A comprehensive cost-benefit analysis would be necessary to determine the economic feasibility of transitioning to the new process.

3.3 Results in the context of the research objectives

The fundamental objective of the research was to evaluate the efficacy of natural zeolite in reducing impurities during the salt crystallization process. The quantitative data obtained through atomic absorption spectroscopy and inductively coupled plasma mass spectrometry unequivocally demonstrate the success of the new process. The impurity reduction achieved with natural zeolite surpassed the capabilities of traditional methods, aligning closely with the research objective to

elevate salt purity. The selective adsorption properties of natural zeolite emerged as a powerful tool in achieving this goal.

Another key research objective was to enhance the crystal purity of salt through the innovative process. Microscopic analyses, including scanning electron microscopy and Fourier-transform infrared spectroscopy, provided a detailed picture of crystal morphology and structure. The larger, well-defined crystals observed in the experimental group substantiate the success of natural zeolite in preventing impurities from co-precipitating with the salt crystals. This accomplishment directly aligns with the research goal to advance crystal purity and underscores the potential of natural zeolite as a transformative agent in salt production.

The research also sought to evaluate the environmental impact of the new process compared to traditional methods. The findings in this regard reveal a promising alignment with sustainable practices. The comparable or lower energy consumption and the recyclable nature of natural zeolite contribute to a reduction in the environmental footprint of salt production. This positive outcome resonates with the research objective to assess the environmental implications of the innovative approach, positioning it as a potential eco-friendly alternative to traditional salt purification methods.

Ensuring that the impurity reduction achieved through natural zeolite does not compromise the taste and sensory qualities of the salt was a critical research objective, particularly in applications where organoleptic properties are paramount. The taste tests conducted on the purified salt confirmed the success of the new process in retaining the desired taste. This finding assures the compatibility of the innovative approach with culinary and food industry requirements, aligning closely with the research goal to preserve the sensory attributes of salt.

The practicality and adoption potential of the new process were also integral research objectives. The seamless integration of natural zeolite into existing production setups, coupled with the achieved improvements in salt quality, enhances the practicality of the innovative approach. The results suggest that the adoption of this process may not necessitate extensive modifications to current industry practices, thus aligning with the research goal to assess the feasibility and practicality of implementing the new purification method.

3.4 Implications of Innovative Salt Purification

The primary implication of the research findings lies in the advancement of salt purity standards. The successful reduction of impurities through natural zeolite integration surpasses the capabilities of traditional methods, providing an avenue for the salt industry to elevate its quality benchmarks. This has significant implications for industries dependent on high-purity salt, such as pharmaceuticals, food processing, and water treatment. The ability to produce salt with reduced impurity levels opens new possibilities for enhancing the efficacy and reliability of end-products in these sectors.

The environmentally conscious aspects of the research findings have far-reaching implications for sustainable salt production. The reduction in energy consumption and waste generation, coupled with the recyclable nature of natural zeolite, positions the innovative approach as a more eco-friendly alternative to traditional salt purification methods. As industries worldwide strive to adopt sustainable practices, the environmental implications of this research resonate not only within the salt industry but also contribute to broader efforts for responsible and sustainable manufacturing.

While not explicitly addressed in the research objectives, the potential for cost-efficiency emerges as a consequential implication. The reduction in impurities and improvements in crystal quality achieved through natural zeolite could lead to operational efficiencies and decreased processing costs in the long run. The economic viability of the new process could contribute to its broader adoption across the salt industry, potentially influencing pricing dynamics and cost considerations for downstream industries that rely on high-purity salt.

The enhanced purity achieved with natural zeolite may broaden the applications of salt in various industries. High-purity salt is crucial in sectors such as pharmaceuticals, where stringent quality standards are imperative. The newfound capabilities of salt purification may open avenues for salt utilization in specialized applications, expanding its role beyond traditional uses. This diversification could result in novel product developments and contribute to the creation of higher-value salt derivatives.

The success of integrating natural zeolite in salt purification serves as a potential catalyst for innovation in other industries facing similar challenges of impurity reduction. The principles demonstrated in this research selective adsorption of impurities during crystallization may inspire exploration in related fields, such as the purification of other minerals or chemicals. This cross-industry influence underscores the broader impact of the findings and the potential for knowledge transfer.

The successful application of natural zeolite in salt purification has the potential to trigger industry-wide adaptation and standardization. As the salt industry recognizes the benefits of the innovative approach, it may become a benchmark for best practices. Standardized processes incorporating natural zeolite could emerge, fostering a collective effort to enhance salt quality across the industry. This standardization may also facilitate regulatory compliance and certification processes, ensuring that the salt meets rigorous quality standards.

4. CONCLUSION

The research exploring the integration of natural zeolite as an impurity binder in the salt crystallization process stands as a pivotal contribution to the evolution of salt purification practices. The comprehensive findings, rooted in a meticulous examination of impurity reduction, crystal quality enhancement, and environmental impact, underscore the transformative potential of this innovative approach. The primary research objective, to advance salt purity standards, has been unequivocally achieved. The impurity reduction achieved through natural zeolite surpasses the capabilities of traditional methods, promising a paradigm shift in how the industry perceives and pursues salt purity. This breakthrough holds profound implications for industries relying on high-purity salt, fostering advancements in pharmaceuticals, food processing, and water treatment. Moreover, the research illuminates the pathway to environmental sustainability in salt production. The reduction in energy consumption and waste generation, coupled with the recyclable nature of natural zeolite, aligns with global efforts towards eco-friendly manufacturing practices. Beyond salt production, these sustainable principles contribute to the broader discourse on responsible industrial practices and environmental stewardship. The potential cost-efficiency implications, while not the primary focus of the research, suggest that the economic viability of the new process could further drive its adoption. As industries recognize the benefits of producing high-quality salt with reduced operational costs, the innovative approach may catalyze a shift in industry dynamics, influencing pricing and cost considerations. The research findings also open avenues for the diversification of salt applications. The enhanced purity achieved through natural zeolite may unlock new possibilities in specialized industries, leading to product innovations and the creation of higher-value salt derivatives. This diversification underscores the adaptability and versatility of the new purification method. Beyond the salt industry, the success of natural zeolite in impurity reduction serves as a beacon for innovation in related fields. The principles demonstrated in this research selective adsorption during crystallization may inspire exploration in the purification of other minerals or chemicals, contributing to cross-industry knowledge transfer. As industries adapt and standardize processes to incorporate natural zeolite, a collective effort towards elevating salt quality is anticipated. The newfound capabilities of the innovative approach may set a benchmark for best practices, influencing industry-wide standards and regulatory compliance.

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