

## Development of technology for obtaining high-purity sodium chloride with induced impurity removal and process modeling

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<p>Received: November 7, 2025 Peer-reviewed: November 19, 2025 Accepted: January 12, 2026</p>	<p><b>ABSTRACT</b> High-purity NaCl is required for chemical processes. Halite from the South Kazakhstan Bakhyt Tany deposit contains <math>\text{CaSO}_4</math> and <math>\text{Ca}^{2+}/\text{Mg}^{2+}</math> that degrade quality and operability. The article presents statistical processing and modeling of impurity deposition with phosphate ions using an automated calculation process. A stoichiometric amount of <math>\text{Na}_3\text{PO}_4</math> was added to the NaCl 315 mol/dm<sup>3</sup> brine, stirred for 25-30 minutes, precipitated for 30 minutes, and filtered. Sulfate was quantified by barium-sulfate turbidimetry; residual <math>\text{Ca}^{2+}/\text{Mg}^{2+}</math> in the filtrate was measured titrimetrically. The Excel 2000 workbook performs coefficient estimation, significance testing, model adequacy testing, and error analysis. Response optimisation is also carried out through protected input fields. The resulting second-order models are adequate within the studied range of factors, reflect significant main effects and interactions, and predict optimal process modes, which have been confirmed experimentally. Under optimized conditions, removal reached 99.9% for <math>\text{Ca}^{2+}</math> and 99.8% for <math>\text{Mg}^{2+}</math>. Sulfate ions remained at trace levels in the NaCl product. The framework enables reproducible parameter selection and provides a basis for integrating near-zero-waste handling of co-products in subsequent process design.</p>
	<p><b>Keywords:</b> phosphate-induced precipitation, high-purity sodium chloride, modeling &amp; statistical analysis, near-zero-waste flowsheet, Ca/Mg ions removal.</p>
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### Introduction

Sodium chloride is one of the most important reagents in the chemical industry and one of the most common mineral salts. Of all the Asian countries, Kazakhstan has the largest number of salt lakes [1]. The salt deposits in southern Kazakhstan have a high sodium chloride concentration and also contain sodium sulphate, as well as calcium and magnesium salts in the form of chlorides and sulphates. In deposits closer to the west, such as Inder, Chelkar, and Satimola, the mineral also contains potassium chloride [[2],[3]].

The price of sodium chloride is directly dependent on its purity [4]. Sodium chloride is found in a solid mineral state in nature. In most cases, insoluble residue and calcite magnesium ions crystallise into the mineral along with sodium chloride [[5], [6]]. Consequently, it is imperative to

dissolve the mineral and subsequently precipitate the residual ions [7]. The conventional methodologies employed for the purification of sodium chloride encompass the utilisation of sodium bicarbonate and limestone. However, to obtain high-purity sodium chloride by these methods, the process must be multi-stage [[8],[9]].

After precipitation, any solid particles that are insoluble in the solution are removed by filtration. The crystallisation of sodium chloride allows pure salt to be separated from impurities; this process is also subject to the kinetic laws related to solubility and temperature [10]. The technological processes of natural salt raw materials are determined by the final equilibrium states of the processed raw materials' components and the introduced reagents, as well as by kinetic factors. The latter either hinders or facilitates the implementation of technical solutions. The kinetics of dissolution processes

depend on various factors, including the nature and composition of solids, the composition and temperature of solutions, the size and shape of crystals, and the instrumental conditions of dissolution [11].

Understanding the kinetics of the process of purifying sodium chloride from calcium and magnesium ions is key to developing effective technologies for producing a high-purity product. Understanding the reaction rate, mechanism, and factors affecting the process enables the purification conditions to be optimised and salt of the required purity to be obtained [[12], [13]]. Using mathematical modelling and experiments helps control the process more accurately and achieve the desired results. The precipitation rate depends on the concentration of the reagent, the temperature, and the reaction time [14]. The purification of saturated brines containing sodium chloride from calcium and magnesium is of great importance for a number of industrial processes. These include the production of chlorine and alkali, as well as food and pharmaceutical salts.

As demonstrated in the studies conducted by Mi et al. [15], Bouaziz et al. [16], and Pérez-González et al. [17], elevated ion concentrations, in conjunction with the presence of competing anions such as sulfate, have been shown to impede the process of calcium and magnesium precipitation. A variety of purification methods are employed in industrial settings, including the lime-soda method and selective precipitation using phosphates or carbonates. However, magnesium precipitates to a greater extent than calcium and requires stricter pH control. Despite the incorporation of a sufficient quantity of reagent, magnesium may persist in solution. Consequently, a combination of reagents and multi-stage treatment is frequently employed in practice. Presently, the potential for the utilisation of impurities as valuable resources is a subject that is being subjected to actively studied. Precipitation of magnesium from brines is a promising area of research. As research has shown, [[15], [16]]. The brine purification process can be integrated with the production of magnesium salts and magnesium hydroxide. Magnesium salts have a wide range of applications, including in the production of materials or fertilizers. Studies have shown that the effectiveness of purification from impurities depends not only on the choice of reagent, but also on consideration of kinetic factors such as time, temperature, and mixing speed.

The objective of the present study is to develop and validate mathematical models of the purification of sodium chloride solutions from

calcium and magnesium ions by sodium phosphate and to perform statistical analysis of the resulting datasets. To enable optimization toward a high-purity NaCl product, we further identify and quantify the factors controlling the rate and efficiency of impurity precipitation. In parallel, we design and assess a near-zero-waste flowsheet that converts phosphate-bearing by-streams into fertilizer co-products. The combined modeling, statistical treatment, and flowsheet evaluation provide a basis for comparative benchmarking against conventional purification routes.

### Experimental part

The salt of the South Kazakhstan region of the Bakhyt Tany deposit was selected for the study. The quantification of sulfate ions was achieved through the implementation of barium sulfate turbidimetry. The content of calcium and magnesium ions was measured using EDTA titration. Microstructure of the samples and elemental analysis were performed using a JSM 6610 LV scanning electron microscope manufactured by the Japanese company JEOL, using the INCA Energy 450 energy dispersive microanalysis system. The measurement accuracy was within 0.01%.

In the process of cleaning the brine from impurities, phosphate ions were used as a precipitator. A saturated salt solution of halite with a concentration of 315 mol/dm<sup>3</sup> was prepared for the experiment. A stoichiometric amount of sodium phosphate was added to the concentrated solution to precipitate calcium and magnesium salts. The resulting mixture was continuously stirred in a thermostat for 25-30 minutes, then the particles were allowed to settle for 20-25 minutes and filtered. The filth was rinsed with clean water. The remains of insoluble salt and insoluble calcium and magnesium compounds settled on the filter in the form of sediment. The amount of calcium and magnesium ions present in the filtered brine was determined by titration with EDTA. The NaCl solution thus obtained is then employed in the treatment and drying of the target product.

The objective of the present study is to automate the processing of research results. To this end, a program for a personal computer has been developed. The program is based on MS Excel 2000 running on Windows. This development allows you to quickly obtain all the necessary calculation results online. This, in turn, made it possible to accurately determine the optimal conditions for the ion deposition reaction. The programme has been developed in the form of an Excel workbook. It is

evident that within the confines of the book, on a specific page, ancillary materials are present. These materials encompass matrices of intermediate values, formulae for calculating parameter b, and statistical processing, among others. It is important to note that all fields on this page, with the exception of input fields, are protected from random changes. The following elements are designated as input fields: a column for entering output Y values; a row for entering input parameters X on a natural scale, utilised in the search for the optimal mode; and a field for entering the experimental output value obtained after laboratory testing of optimisation results. In addition to the current input values, the main sheet displays: coefficient estimates b; significant coefficients according to the Student's criterion; the result of the Fischer criterion adequacy test; for each experiment, there are absolute and relative approximation errors when using all b and only significant b; average total relative error in the sample; the result of the search for the optimal mode; absolute and relative error for computational and experimental verification.

### The discussion of the results

The mineral halite from the Bakhyt-Tany deposit in the Sozak district of the South Kazakhstan region was selected for detailed study. The sodium mineral present in the selected deposit is distinguished by its low impurity content, its superficial location, and its high sodium chloride concentration. Preliminary research by the authors [18] indicates that the moisture content of the samples ranges from 0.6 to 3%. It was possible to calculate the approximate salt composition of the halite mineral based on the results obtained. The composition of the solution is as follows: calcium sulfate ( $\text{CaSO}_4$ ) at 2.5%, magnesium sulfate ( $\text{MgSO}_4$ ) at 0.18%, magnesium chloride ( $\text{MgCl}_2$ ) at 0.37%, and sodium chloride ( $\text{NaCl}$ ) at 88.4%. The mineral has been found to contain up to 2-3% by mass of insoluble residue.

In a previously published paper [[17], [18]], we presented experimental results on the purification of  $\text{NaCl}$  solutions from  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions using sodium phosphate. The present article is devoted to the statistical processing of the aforesaid experimental data and the mathematical modelling of the process, with a view to identifying significant factors, constructing predictive regression models, and optimising the conditions for obtaining a high-purity product. Consequently, the present study extends the findings of [18] from the level of a laboratory experiment to that of a quantitatively

verified model and computational optimisation, whilst also addressing integration into a near-zero-waste scheme.

A study was conducted to ascertain the most effective method of purifying the natural mineral of the Bakhyt Tany ore – halite. The study incorporated various factors into its mathematical planning, including the chemical composition of the raw materials, the degree of purification, the temperature, and the time of purification. The study aimed to determine the dependence of the degree of purification Y on such factors as: a) temperature  $X_1$  (K), b) time  $X_2$  (min), and c) degree of purification  $X_3$  (%). In order to establish the dependency sought, it was necessary to ascertain the value parameters in the mathematical model that adequately described the cleaning process. These were given in the form of the regression equation below:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_{11}X_1^2 + B_{22}X_2^2 + B_{33}X_3^2 + B_{12}X_1X_2 + B_{13}X_1X_3 + B_{23}X_2X_3 \quad (1)$$

The determination of the value parameters b was achieved by utilising the method of planning a second-order rotatable experiment. Following a comprehensive analysis of the system in question, the range of possible changes to the factors was determined and is presented in Table 1 and Figure 1. Based on the results of the experiments, the optimal parameters of the technological regime were determined, and they are shown in Table 2. The processing of the experimental results was conducted in accordance with the prevailing methodology.

The following table presents the results of studies undertaken to ascertain the levels of factors and their ranges of variation.

**Table 1** - Results of studies to determine the level of factors and their ranges of variation

Factors	$X_1$	$X_2$	$X_3$
Lower level (-1)	10	20	90
High Level (+1)	45	25	105
Zero level (0)	27.5	22.5	97.5
Variation interval ( $\Delta X$ )	17.5	2.5	7.5
Shoulder+ $\alpha$	56.935	26.705	110.115
Shoulder- $\alpha$	-1.935	18.295	84.885

**Table 2** - Calculated optimal parameters of the technological regime

Nº	$X_1$ , °C	$X_2$ , min	$X_3$ , %	Y, degree of purification
1	25	30	95	99.9

Coefficients of the model				Coefficients of the model			
	At:	all coefficients	significant		At:	all coefficients	significant
B0		97.88290	97.88290	B0		99.07944	99.07944
B1	X1	-0.02928	0.00000	B1	X1	0.75263	0.75263
B2	X2	-1.22742	-1.22742	B2	X2	-0.27084	0.00000
B3	X3	-0.32341	-0.32341	B3	X3	-0.42955	-0.42955
B11	X1*X1	0.53413	0.53413	B11	X1*X1	-1.40842	-1.40842
B22	X2*X2	-1.28667	-1.28667	B22	X2*X2	-1.12557	-1.12557
B33	X3*X3	0.07451	0.07451	B33	X3*X3	-0.78970	-0.78970
B12	X1*X2	0.47500	0.47500	B12	X1*X2	-0.13750	0.00000
B13	X1*X3	-0.92500	-0.92500	B13	X1*X3	0.11250	0.00000
B23	X2*X3	-0.32500	-0.32500	B23	X2*X3	-1.73750	-1.73750
The number is significant.coefficient.			9	The number is significant.coefficient.			7
The calculated F-criterion			4.1	The calculated F-criterion			4.5
Tabular F-criteria			5.1	Tabular F-criteria			5.1

The equation is adequate!

(a)

The equation is adequate!

(b)

**Figure 1** – Coefficients of the quadratic regression model and the experimental plan in coded variables (X1–X3); the values of all significant coefficients, a matrix of dimensionless inputs, as well as the result of the adequacy test by the F-criterion are shown: (a)Mg; (b) Ca

During the mathematical processing of the fractional factor experiment data, the coefficients of the regression equations were estimated, and the following second-order models were obtained in encoded coordinates:

$$Y = 97,88290 - 0,02928X_1 - 1,22742X_2 - 0,32341X_3 + 0,53413X_1^2 - 1,28667X_2^2 + 0,7451X_3^2 + 0,47500X_1X_2 - 0,92500X_1X_3 - 0,32500X_2X_3 \quad (2)$$

$$Y = 99,07944 + 0,75263X_1 - 0,27084X_2 - 0,42955X_3 - 1,40842X_1^2 - 1,12557X_2^2 - 0,78970X_3^2 - 0,13750X_1X_2 + 0,11250X_1X_3 - 1,73750X_2X_3 \quad (3)$$

The obtained regression equations (2) and (3) adequately describe the behavior of the system in the studied range of factors (verification by the Fisher criterion:  $F_{\text{calculation}} < F_{\text{table}}$ ). The signs and relative values of the coefficients are consistent with chemical expectations: the linear contribution of  $X_2$  and negative quadratic terms for  $X_1$ – $X_3$  indicate the existence of internal limitations on "supersaturation" and optimal dose/time windows beyond which precipitation efficiency decreases. The presence of statistically significant interactions confirms that process management requires balancing factors rather than independently adjusting them. The mean relative approximation errors are negligible, and the discrepancy between

the calculated and verified (laboratory) Y output is within the stated margin of error. This renders models a viable engineering tool for operational forecasting of the degree of purification and the selection of modes. To assess the reproducibility of the results, the variation in the degree of purification of the solution from magnesium and calcium ions was analysed. The measurements were performed in three parallel repetitions ( $n = 3$ ), and the obtained values are presented as fluctuation intervals. The degree of purification from magnesium ions after optimisation was 98.5–99.8%, which corresponds to a relative error of approximately  $\pm 0.6\%$ . Similarly, the degree of purification from calcium ions was in the range of 98.2–99.8%, which corresponds to an error of approximately  $\pm 0.8\%$ . Such small fluctuations in the results indicate high stability and reproducibility of the process.

#### *Flow chart and its comparison with analogues*

The conventional protocol for the purification of salt rocks and brines involves a series of operations, including rock crushing, dissolution, removal of insoluble residue, precipitation of impurities, and filtration. In patent KG 1428 (C01D 3/08, 03/30/2012) [19], it is proposed that barium hydroxide be introduced into a heated (50–70 °C) solution at a sulfate-ion ratio of 1.37–1.50:1. The method's primary benefits are twofold: firstly, it accelerates the process by eliminating multi-stage

deposition; secondly, it reduces consumption of reagents and energy.

The principal disadvantage of the barium approach is the use of toxic  $\text{Ba}(\text{OH})_2$  (hazard class 2), which complicates the achievement of a reagently pure salt and increases safety and waste management requirements. Furthermore, in the presence of  $\text{Ba}(\text{OH})_2$  and subsequent neutralisation of  $\text{HCl}$ , soluble  $\text{CaCl}_2$  and  $\text{MgCl}_2$  are formed; thus, calcium and magnesium pass into solution and are not removed from the sodium chloride matrix.

An evaporative method for producing commercial salt is also widely known [20] [RU 2075440, C01D 3/06, 1997], which provides "Extra" quality for the food industry ( $\text{Ca} \approx 0.02$  wt.%,  $\text{Mg} \approx 0.01$  wt.%,  $\text{K} \approx 0.02$  wt.%,  $\text{SO}_4^{2-} \approx 0.16\%$  by weight). Nevertheless, this level of purity is inadequate for the tasks of fine organic synthesis, electrochemistry, and microelectronics, where lower levels of impurities and the absence of corrosive acid residues are required.

The closest method to ours is the RU 2495825 method (C01B 3/14, 10/20/2013) [21], which involves the purification of a saturated  $\text{NaCl}$  solution at  $25^\circ\text{C}$  from mechanical impurities. This is achieved through a series of processes including evaporation, crystallisation, centrifugation, subsequent washing and drying. Before the process of evaporation, the solution is subjected to treatment with  $\text{HCl}$  at a concentration of 1.0–1.5 wt. %. This is followed by the process of boiling and the washing of the crystals with high-purity water. The process is characterised by multifarious disadvantages, including but not limited to:

- Multi-stage operation, which is both inefficient and costly.
- The use of concentrated hydrochloric acid, which is liable to cause corrosion of equipment and necessitates additional flushing with expensive water, thus increasing capital and operating costs. Existing solutions are characterised by the utilisation of toxic reagents ( $\text{Ba}(\text{OH})_2$ ), the provision of food but not chemical purity, or the requirement of acid treatment and energy-intensive steaming. It is imperative that a technologically simple, safe, and economical scheme is implemented for the selective removal of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions, without the introduction of corrosive components.

The proposed method is based on the selective precipitation of calcium and magnesium in the form of insoluble phosphates during the treatment of brine with sodium phosphate. The technology combines mechanical desalination, dissolution, and circulation of saturated  $\text{NaCl}$  fluxes with single-stage

stoichiometric phosphate injection and subsequent gravity filtration phase separation.  $\text{CaSO}_4$  is an undesirable impurity in the composition of salt and insoluble residue. In the production of soda, it increases the formation of scale in evaporators and reduces the efficiency of the process. There are special purity requirements for food salt.

Calcium sulfate is a valuable raw material. Recent studies [[22], [23]] have shown that it is widely used in various fields, including the production of building materials, ceramics, soil improvement products, and asphalt concrete composites. Thus, the removal of  $\text{CaSO}_4$  from halite has two main advantages. The first is to improve the quality of salt. Secondly, the creation of opportunities for processing and reuse of this by-product in other industries.

Based on the results of the study, a technological scheme was developed, shown in Figure 2. The production process of table salt begins with loading salt into a mixer (1). Then, mechanical impurities are removed using a circulating saturated solution, which is heated to a temperature of  $20\text{--}25^\circ\text{C}$  and remains for 30 minutes.

Throughout the entire process, a constant ratio of solution and salt is maintained — 3:1 by weight. The resulting suspension is separated by sieving on a sieve (2). The solution containing mechanical impurities passes through a walnut filter (3), where it is cleaned. This solution is returned to wash the sodium chloride salt.

The ore that has been washed is dissolved in water, and the resulting solution is passed through a filter press to remove any remaining water. Then the solution reaches a saturation state in the reactor at a temperature of  $25^\circ\text{C}$ . At this point, sodium phosphate is added to the solution in an amount equal to 95% of the stoichiometric norm. This is necessary for the precipitation of calcium and magnesium impurities. The resulting suspension is then settled in a sump (5), where it is divided into two layers. The top layer containing impurities is a condensed pulp, which is filtered in a filter (6). The filtered sludge is removed, and the filtrate and washing water are returned to the reactor (4) for reuse.

The clarified part of the solution is drained from the sump and enters the spray dryer (7), where it is dried using flue gases at a temperature of  $100\text{--}110^\circ\text{C}$ . As a result of this process, sodium chloride crystallizes. The dried crystalline product is transferred from the dryer to the screw feeder (9), where it undergoes a cooling period, and then packed.



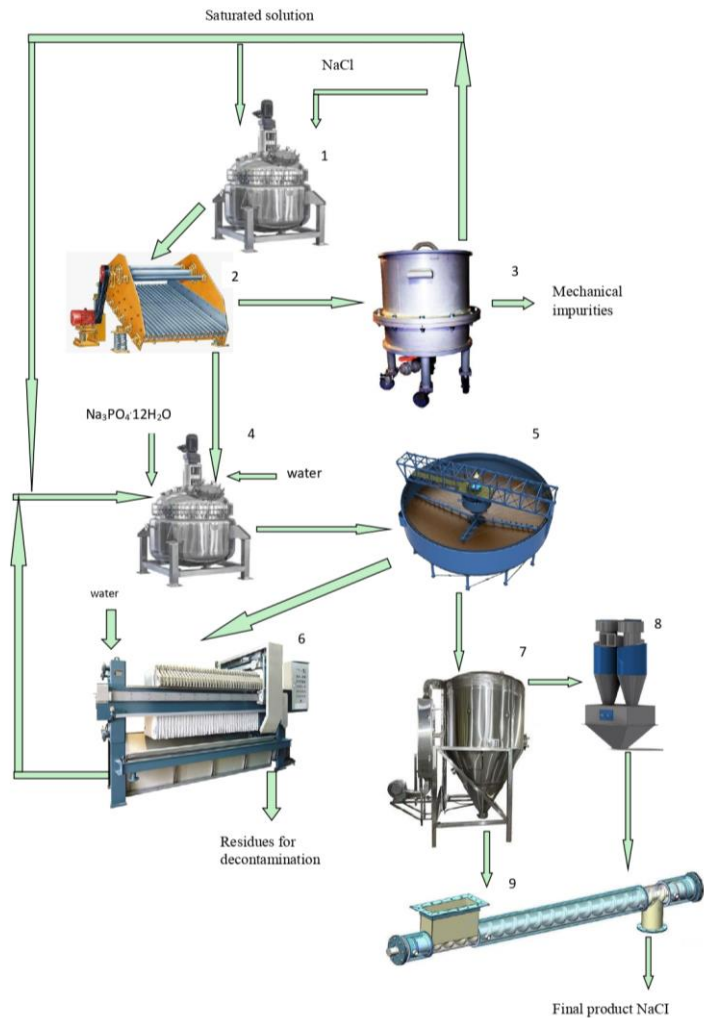


Figure 2 - Technological scheme

The proposed method has several advantages over the existing method. Firstly, it does not require the use of concentrated hydrochloric acid in the cleaning process, which avoids corrosion of the equipment and eliminates the need for thorough washing of sodium chloride crystals with high-purity water. Secondly, this method significantly simplifies the technological process and reduces energy costs.

This scheme provides three valuable products:

- 1. Pure NaCl
- 2. Building composite  $\text{CaSO}_4$
- 3. Phosphorites, which can be used as raw materials for fertilizers

In addition, solutions are recycled during the processing process, which helps to reduce costs and minimize toxic by-products. This technological approach is characterized by almost zero waste, which is an important aspect of sustainable production. During the processing process, impurities are converted into resources, which effectively eliminates their waste status.

As illustrated in Figure 3, the spectrogram of the resulting product is evident. As demonstrated in

Table 3, the analysis of the elements has been shown to confirm the high degree of purity of the sodium chloride obtained.

Table 3 - Elemental composition of the obtained sodium chloride

Element	Mass %	Atom, %
Na	36.87	47.39
Cl	63.13	52.61

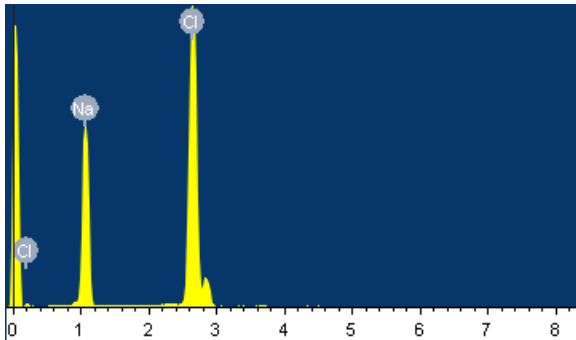


Figure 3 - Spectrogram of the obtained sodium chloride

Cost analysis showed that the main costs of obtaining one ton of purified sodium chloride are related to the price of the feedstock and reagent, sodium phosphate. Under optimal conditions, the cumulative variable costs amount to KZT 25,782 per ton, and the permanent costs amount to KZT 5,000 per ton. This results in a total cost of about 30,782 tenge per ton. Taking into account the trade margin of 15%, the selling price of the product is 35,399 tenge per ton. Thus, the expected profit from the sale of one ton of purified sodium chloride is approximately 4,600 tenge. Calculations confirm that the use of sodium phosphate as the main reagent significantly affects the cost of the process. However, the optimized technology remains economically beneficial. The absence of significant energy costs and a small amount of waste make this method more preferable from an environmental and economic point of view compared to alternative cleaning methods.

### Conclusions

A statistical and mathematical model of phosphate-induced purification of NaCl brines from  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  has been developed and verified; second-order models (2)-(3) are adequate according to the Fisher criterion and technologically interpretable.

The identification of dominant factors and significant interactions has been achieved, thereby excluding independent parameter setting and requiring coordinated mode management.

The calculation of optimisation, based on the models, provides the target removal rates: The concentrations of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  were found to be 99.9% and 99.8%, respectively, within the specified factor windows.

It has been demonstrated that  $\text{SO}_4^{2-}$  does not integrate into the halite lattice and is concentrated in the mother cell; only trace amounts of sulfates remain in solid NaCl, which confirms the consistency of the model with product analysis.

A scheme for the reduction of waste, with three distinct streams, has been established. The target product is pure NaCl,  $\text{CaSO}_4$ , with mechanical impurities, has been identified as a suitable building material/filler. Phosphates of calcium and magnesium are considered suitable as co-products for use as fertiliser.

In comparison with conventional acid-evaporation and barium methods, the proposed scheme eliminates the use of toxic reagents and corrosive media, reduces the number of stages, water capacity and OPEX, while maintaining or exceeding the purity level.

The implementation of an application tool in the form of an Excel workbook has been undertaken for the purpose of facilitating instant calculations, optimising search functions and expediting the verification of modes. This development serves to streamline the transfer of results to the production site.

The dependencies obtained provide direct engineering regulations, including factor operating windows, sensitivity gradients, stopping criteria, and quality control metrics.

The original experimental arrays from the previously published work have been rethought, and through statistical processing and modelling they have been transformed into a predictive optimisation tool ready for scaling.

The environmental impact of the process is evident in the transformation of "impurities" into resource flows, as well as the closure of brine circulation. These factors serve as indicators of a practical, waste-free process. This section is not mandatory but can be added to the manuscript if the discussion is unusually long or complex.

The proposed model and scheme ensure industrially significant purity of NaCl with a minimum of stages and waste, as well as create economically useful co-products ( $\text{CaSO}_4$  and Ca/Mg phosphates). This makes the technology competitive and sustainable for implementation in modern chemical technology chains.

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**Conflicts of Interest.** On behalf of all authors, the corresponding author declares that there is no conflict of interest.

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## Қоспаларды кетіруді индукциялау арқылы жоғары тазалықтағы натрий хлоридін алу технологиясын әзірлеу және процесті модельдеу

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<p>Мақала келді: 7 қараша 2025 Сараптамадан өтті: 19 қараша 2025 Қабылданды: 12 қаңтар 2026</p>	<p><b>ТҮЙІНДЕМЕ</b></p> <p>Химиялық процестерге жоғары тазалықтағы NaCl қажет. Дегенмен Оңтүстік Қазақстандағы Бақыт таңы кен орнынан алынған галиттің құрамында <math>\text{CaSO}_4</math> және <math>\text{Ca}^{2+}/\text{Mg}^{2+}</math> бар, олар өнім сапасын төмендетеді. Бұл мақалада фосфат иондары арқылы қоспалардың тұнуын автоматтандырылған есептеу процесінің көмегімен статистикалық өңдеу және модельдеу ұсынылады. 315 моль/дм<sup>3</sup> NaCl тұзды ерітіндісіне стехиометриялық мөлшерде <math>\text{Na}_3\text{PO}_4</math> қосылды, қоспа 25–30 минут араластырылды, 30 минут тұндырылды және кейін сүзілді. Сульфаттың мөлшері барий сульфатын қолданатын турбидиметриялық әдіспен анықталды; фильтраттағы қалдық <math>\text{Ca}^{2+}/\text{Mg}^{2+}</math> титриметриялық әдіспен өлшенді. Excel-2000 жұмыс кітабында қорғалған енгізу өрістері арқылы коэффициенттерді бағалау, Стюденттің t-сынағына негізделген мәнділікті тексеру, Фишердің сәйкестік критерийі, қателерді диагностикалау және қорғалған енгізу өрістерін пайдаланып жауап бетін оңтайландыру жүзеге асырылды. Нәтижесінде алынған екінші ретті модельдер зерттелген факторлық кеңістікте адекватты болып шықты, маңызды негізгі және өзара әрекеттесу әсерлерін ашып көрсетті және тәжірибе жүзінде расталған жұмыс аймақтарын болжады. Оңтайландырылған жағдайларда <math>\text{Ca}^{2+}</math> үшін жою тиімділігі 99,9%-ға, <math>\text{Mg}^{2+}</math> үшін 99,8%-ға жетті, ал NaCl өніміндегі сульфат мөлшері болмашы деңгейде қалды. Ұсынылып отырған әдіс оптималды параметрлерді таңдауға мүмкіндік береді және процесті кейін жобалау кезеңінде қалдықсыз технологиялық үрдісті құрастыруға негіз болады.</p>
	<p><b>Түйін сөздер:</b> фосфаттармен тұндыру, жоғары тазалықтағы натрий хлориді, модельдеу және статистикалық талдау, қалдықтардың нөлге жақын деңгейі, <math>\text{Ca}/\text{Mg}</math> иондарын жою.</p>
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## Разработка технологии получения хлорида натрия высокой чистоты с индуцированием удаления примесей и моделирование процесса

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<p>Поступила: 7 ноября 2025 Рецензирование: 19 ноября 2025 Принята в печать: 12 января 2026</p>	<p><b>АННОТАЦИЯ</b></p> <p>Для химических процессов требуется высокочистый NaCl, однако галит с южно-казахстанского месторождения Бахыттаны содержит <math>\text{CaSO}_4</math> и <math>\text{Ca}^{2+}/\text{Mg}^{2+}</math>, которые ухудшают качество и работоспособность. В этом исследовании представлена статистическая обработка и моделирование очистки, вызванной использованием фосфатов, с использованием автоматизированного процесса расчетов. В статье представлена статистическая обработка и моделирование осаждение примесей с фосфат ионами, с использованием автоматизированного процесса расчетов. В рассол NaCl 315 моль/дм<sup>3</sup>, добавляли стехиометрическое количество <math>\text{Na}_3\text{PO}_4</math>, перемешивали в течение 25–30 мин, осаждали в течение 30 мин и фильтровали. Количественное определение сульфата проводили с помощью турбидиметрии сульфатом бария; остаточное содержание <math>\text{Ca}^{2+}/\text{Mg}^{2+}</math> в фильтрате определяли титриметрически. Рабочая тетрадь Excel-2000 реализует оценку коэффициентов, проверку значимости на основе t-критерия Стюдента, критерий адекватности Фишера, диагностику ошибок и оптимизацию поверхности отклика с помощью защищенных полей ввода. Полученные в результате модели второго порядка адекватны в рамках изучаемого факторного пространства, выявляют существенные основные эффекты и эффекты взаимодействия и предсказывают рабочие периоды, которые были экспериментально подтверждены. В оптимизированных условиях удаление достигло 99,9% для <math>\text{Ca}^{2+}</math> и 99,8% для <math>\text{Mg}^{2+}</math>, в то время как содержание сульфата в продукте NaCl оставалось незначительным. Система позволяет воспроизводимо подбирать параметры и обеспечивает основу для интеграции процессов переработки побочных продуктов с практически нулевым уровнем отходов при последующем проектировании процесса.</p>
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	<b>Ключевые слова:</b> осаждение фосфатами, высокочистый хлорид натрия, моделирование и статистический анализ, технологическая схема, близкая к нулевому уровню отходов, удаление ионов Ca/Mg.
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