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Review article

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Prospects for the use of soda production waste in various industries

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Abstract

This paper presents a review and analysis of scientific articles and patents addressing the disposal and processing of soda production waste. Examples of methods for reducing the toxicity of sludge, using waste in construction (including road construction), and processing it into chemical compounds are provided. Particular attention is paid to the use of sludge for soil reclamation. The ammonia-soda process (the Solvay process) for producing soda ash is the predominant method worldwide. A significant drawback of this process is the generation of hazardous production waste, which necessitates compliance with environmental requirements and regulations during storage and processing. Russian practices for managing soda production waste lag behind European ones due to low prices for primary natural raw materials, the heterogeneity of waste composition and properties, the need for preliminary waste treatment, and the low level of environmental payments by enterprises for waste disposal. Tightening environmental safety requirements for soda ash production waste and the high cost of maintaining settling ponds are driving the development of processing methods. The choice of processing method depends on the plant's location, energy capacity, and the company's financial condition. The use of sludge in the production of building materials is limited by the presence of chloride ions, small particle size, thixotropic properties of the material, and variability in sludge composition. Road construction is the most promising avenue in terms of disposal volumes and the use of waste without additional treatment. The use of waste for land reclamation requires a selective approach to site selection and additional research. Despite the wide range of possible applications for soda production waste, the problem of its disposal remains pressing. This is due to the volumes of soda production and the resulting waste, as well as the need for financial investment to implement disposal methods.

Keywords

soda ash production waste; areas of rational use; disposal methods; soil reclamation; environmental safety

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Introduction

The ammonia-soda process for producing soda ash, developed by the Belgian chemist and entrepreneur E.Solvay in the late 19th century, is widely used throughout the world. In Russia, it accounts for 80 % of the total volume of soda produced.

The technological process for producing soda ash includes the following stages:

• Gaseous ammonia and carbon dioxide are passed through a saturated aqueous solution of sodium chloride (the reaction proceeds at 30-40 °C):

$$NaCl + NH_3 + CO_2 + H_2O = NaHCO_3\downarrow + NH_4Cl.$$

• The precipitated sodium bicarbonate (solubility 9.6 g per 100 g of water at 20 °C) is filtered off and calcined at 140-160 °C, resulting in the formation of sodium carbonate:

$$2NaHCO_3 = Na_2CO_3 + CO_2\uparrow + H_2O.$$

The CO_2 formed is returned to the production cycle.

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• The ammonium chloride solution is treated with calcium hydroxide:

$$2NH_4Cl + Ca(OH)_2 = CaCl_2 + 2H_2O + 2NH_3\uparrow.$$

The resulting ammonia is returned to the production cycle.

In this process, a large amount of waste is generated per 1 t of soda ash:

– about 9-10 m^3 of distiller waste with the composition: 110-120 g/l $CaCl_2$, 54-58 g/l NaCl, 21-26 g/l of suspended $Ca(OH)_2$, $CaSO_4$, and $CaCO_3$;

– about 50 kg of sludge resulting from the production of milk of lime and fly ash ($CaCO_3$, CaO);

– about 0.1 m^3 of sludge resulting from brine purification, which contains 240-300 g/l of suspended $Mg(OH)_2$ and $CaCO_3$ [1].

Soda production waste can be hazardous to the environment; therefore, environmental requirements and regulations must be observed when handling it. This article presents a review of scientific articles and patents addressing the problems of disposal and processing of soda production waste.

The study drew on the following scientific electronic libraries: elibrary.ru, CyberLeninka, Google Scholar, ScienceDirect, MDPI, Springer Nature Link, as well as the patent databases of the Federal Institute of Industrial Property and Google Patents. Publications were selected using the keywords “soda ash”, “soda production waste”, “soda waste disposal”, “road construction”, and “reclamation of disturbed lands”. Methods of qualitative analysis and comparison were used.

Results and discussion

One of the first foreign studies on the disposal of soda production waste is a paper published in the proceedings of an international symposium on environmental technologies in developing countries [2]. Soda plant waste in Mersin (Turkey) was proposed for use as a building material (milk of lime, mortar).

The growth in publications on the use of soda production waste began in the 21st century. The most active research in this field is conducted by scientists from China (more than 700 papers), the United States (about 500), India (more than 300), and Japan (more than 200). Among organizations, the leaders include the National Natural Science Foundation of China, the U.S. Department of Energy, the Japan Society for the Promotion of Science, and others [3].

The European Union has developed the Best Available Techniques (BAT) Reference Document (BREF) for the manufacture of large volume inorganic chemicals*, which describes available technologies for preventing and controlling pollution in the production of large volume inorganic chemicals, with an emphasis on solid and other associated products. The BREF focuses on large volume production of inorganic chemicals that results in solid products or uses other processes not covered by other BREF, such as the LVIC-AAF BREF (ammonia, acids, and fertilizers). The purpose of the reference document is to provide industrial enterprises with a basis for implementing best practices to minimize the environmental impact of their activities. BAT refers to the most effective and advanced technologies that serve as the fundamental basis for determining emission limit values or overall reductions in emissions and environmental impact.

The reference document contains information on:

• specific processes and technologies used in the production of various inorganic solids;

• environmental performance indicators of existing installations;

• methods for preventing and reducing environmental impact;

• emission and consumption levels associated with BAT;

* Best Available Techniques (BAT) Reference Document for the Large Volumes Inorganic Chemicals – Solids and Others industry. URL: https://bureau-industrial-transformation.jrc.ec.europa.eu/sites/default/files/2019-11/lvic-s_bref_0907.pdf (accessed 16.03.2026).

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• monitoring requirements;
• impacts on various media (air, water, waste).

Examples of the chemicals produced include soda ash (sodium carbonate, including sodium bicarbonate).

The reference document recommends a number of procedures for enterprises to reduce the toxicity of sludge before its disposal or use. Washing the sludge with water reduces the content of soluble salts, while drying the waste facilitates its transportation and re-use. Before discharging distiller waste into fresh water bodies, primary treatment with removal of coarse particles is recommended. When discharged into mineralized water bodies (primarily seas), natural dilution and dispersion of suspended particles occur. In addition, underground disposal of production waste is recommended. The selection of raw materials with a low concentration of heavy metals also reduces the toxicity of the waste.

The Best Available Techniques Reference Document published in Russia* is a standardization document developed as a result of an analysis of technological, technical, and management solutions used in the production of solid and other inorganic chemicals. Section 7 provides information on soda production:

• a description of the technological process currently in use;
• the current level of emissions into the environment;
• determination of best available techniques;
• best available techniques;
• promising technologies.

Although no substantially new technologies in soda ash production based on the ammonia-soda method have emerged since 1977, international experience has informed a number of improvements aimed at reducing waste:

• construction of a distiller waste filtration unit, aimed at solving the problem of soda production waste disposal;
• implementation of an automated control system for soda production to optimize process management and conserve raw material and energy resources;
• implementation of a fluid bed dryer for purified sodium bicarbonate, aimed at improving the consumer qualities of food-grade soda;
• replacement of column equipment components with modernized ones;
• expansion of calcium chloride production to obtain a marketable product from soda ash production effluent.

Russian practices for managing soda production waste, including the use of their resource potential, lag behind European ones. The main reasons are: relatively low prices for primary natural raw materials; the heterogeneity of waste composition and properties; the need for preliminary waste treatment; and the low level of environmental payments by industrial enterprises for waste disposal [4]. However, stringent environmental safety requirements for soda ash production waste and the high cost of maintaining settling ponds are driving the development of processing methods. The choice of a method for processing distiller waste depends on a number of factors: the plant's location, production areas, energy capacity, and the company's financial condition [5].

This article presents a review of current methods and technologies for the processing and use of soda production waste.

Reduction of the toxic properties of waste

Paper [6] presents studies on the effect of the dewatering method on the toxicity of sludge. Dewatering soda production sludge by centrifugation makes it possible to isolate a fine fraction (< 0.5 mm; pH 8.3) that has material potential. Separating dewatered soda production sludge into different size fractions allows methods to be selected for subsequent processing and disposal. For example, dewatered sludge can replace up to 3 % of the mineral powder in hot asphalt concrete mixes.

* Production of Solid and Other Inorganic Chemicals. BAT Reference Document 19-2016. Moscow: BAT Bureau, 2016, p. 314.

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Paper [7] presents the results of studies on sorption processes using the AV-17-8 anion exchange resin: static sorption of chloride ions from the clarified portion of distiller waste and dynamic sorption of calcium and chlorine ions with subsequent regeneration of the anion exchanger with sodium hydroxide solution. The data obtained confirm the feasibility of using the anion exchanger for demineralization of distiller waste, as well as the use of regeneration solutions for lime slaking.

Alkaline wastewater generated during soda production is characterized by high electrolytic conductivity and concentrations of ions: chlorides, sulfates, phosphates, calcium, sodium, magnesium, potassium, and ammonium. Paper [8] presents the results of a study on the efficiency of removing sodium, potassium, calcium, magnesium, and ammonium ions from wastewater using three sorbents: Halosorb, Compakt, and Damsorb K. The process was carried out by a dynamic method with varying wastewater flow through a column packed with sorbent, which made it possible to reduce the concentrations of all the studied cations. It was established that the type of sorbent did not have a significant effect on the removal of any of the ions, but the deposit load had a significant effect on the removal of all the studied ions.

The technology for processing solid waste from soda ash production [9] provides for obtaining low-chloride sludge from distiller suspension during thickening by carbonation with lime kiln gas, followed by treatment with soda-containing solutions and filtration. The resulting mixture is dosed, ground, and dried. This method removes all restrictions on the use of sludge in cement production.

Patent [10] proposes a method for processing distiller waste by treatment with hydrochloric acid or hydrogen chloride at 20-100 °C, with the released carbon dioxide returned to the process. The invention makes it possible to obtain soda without solid waste, as well as an additional amount of carbon dioxide, which reduces the volume and alkalinity of the distiller waste discharged into sludge storage ponds.

Use of waste in the construction industry

Modern studies have shown that the use of sludge for producing building materials is limited by the presence of chloride ions, small particle size, the thixotropic properties of the material, and variability in composition [6, 11, 12].

Paper [13] examines the experience of disposing of solid and liquid soda production waste. It presents the results of research and industrial experience in the production of: lime-belite binder and sand-lime brick based on it; lime-containing binder and cellular concrete based on it; special oil-well cement; aggregates for asphalt concrete; a salt composition; and other applications.

Geopolymer binder, which is an environmentally friendly alternative to traditional cement binders, can be obtained from soda production waste [14]. The inclusion of about 20 % waste provides specimens with maximum compressive strength under the developed curing methods. The addition of waste leads to less shrinkage, a greater number of macropores, earlier strength gain, and a denser microstructure of the geopolymer stone. It has been proven that improving the physical, mechanical, and microstructural characteristics of geopolymer materials by incorporating waste is feasible and effective, providing environmental protection through waste disposal.

The use of distiller waste sludge as an additive for producing alinite cement is promising; its induction period was about 15-20 min, and unlike Portland cement, hydration practically does not stop during this period [15].

An oil-well grouting solution has been developed that contains cement, the residue of distiller waste calcined at 550-650 °C, and unclassified microspheres, with the following component content, wt.%: cement – 43.5-62.5; distiller waste – 0.7-6.2; microspheres – 6.5-19.9; water – the remainder. The grouting solution has reduced density and water separation, and the formed cement stone is characterized by increased strength [16].

For cementing wells in permafrost rocks of Far North fields, a formulation of grouting solution has been proposed based on a gypsum-free binder containing, in addition to clinker, CaO (soda production waste, 10 % of the clinker content), nitrilomethylene phosphonic acid (0.10-0.13 %), and

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Na_2CO_3 (3.8-5.0 %). It has been shown that all characteristics of the stone formed from this grouting solution that are important from a practical standpoint are 2-4 times higher than those of binder compositions based on Portland cement with $CaCl_2$ additive [17].

Paper [18] presents the results of studies on the effect of finely dispersed solid soda production waste (SSPW) on the properties of silicate material and the production of a binder based on it. The composition of the cementing compound of autoclaved silicate materials based on SSPW has been established. Soda production waste is also suitable for other building materials beyond sand-lime brick and cellular concrete, including its use as a mineral powder for asphalt concrete mixes and as a component of complex additives in the production of various cement-based building materials.

In China, it is proposed to use soda production waste, after mixing with other materials, as fill for subgrade. The strength characteristics of the mixtures have been studied in detail, and it has been proven that fly ash and lime mixed with soda waste in a 3:7 ratio increase the strength of the original material by a factor of 6.5. The microstructure of soda waste is similar to that of soil, and its particle size distribution is well suited for mixing with other materials used as subgrade [19].

To improve the properties of raw materials in the manufacture of ceramic products, modification methods are used, including the introduction of technological additives of natural and anthropogenic origin [20]. The possibility of modifying clay raw materials by introducing 5-10 % of the dewatered residue of technical soda ash production waste obtained by the ammonia method has been demonstrated; this residue contains 7.49 % sodium, 0.17 % potassium, 3.27 % magnesium, 25.95 % calcium, 13.08 % chloride ions, and 85 mg/kg vanadium. The mineral composition of the clay material, %: montmorillonite – 13, chlorite – 10, kaolinite – 8, quartz – 54, feldspar – 11, mica – 4. The addition of the dewatered residue to the clay raw material does not change its class of sensitivity to drying. Laboratory ceramic specimens fired at 1000 °C have improved strength and thermal insulation characteristics. The compressive strength of the ceramic is 8-26 % higher, the average density is 0.16-0.31 g/cm^3 lower, and the porosity is 5.7-7.8 % higher. The increase in ceramic strength is due to its structural features associated with the formation of the anorthite phase (66 %) during firing. The technogenic additive contains a large amount of calcium, which participates in the processes occurring during firing, including the formation of anorthite. Wall ceramic products (brick, stone) with performance characteristics meeting the requirements of scientific and technical documentation can be produced from the modified raw material.

The authors of paper [21] have developed a new environmentally friendly and low-carbon cementitious material, SR-GGBS-PG, consisting entirely of soda residue (SR) and phosphogypsum (PG) as synergistic activators for ground granulated blast furnace slag (GGBS). The effects of the SR/GGBS ratio and PG content on paste fluidity, setting time, pH value, and compressive strength were investigated. At a mass ratio of SR, GGBS, and PG of 10:81:9, the compressive strength at 28 days reached 46.15 MPa. Studies of macroscopic properties, mineral composition, and hydration products were conducted. Studies have confirmed that various solid wastes can be effectively utilized to produce environmentally friendly building materials.

Based on an analysis of the formation conditions and physicochemical properties of soda production waste, a review of its applications in building materials, including cements, brick, and road subgrade materials, is presented [22]. The risks and problems associated with the use of the waste in building materials are considered. It has been established that the waste has high alkalinity and calcium content, a small particle size, and a large specific surface area, which makes it a promising raw material in the construction industry. A limitation to the use of the waste is the high concentration of chloride ions, which can reduce the durability of building materials. Currently, there are no effective and environmentally safe methods for removing Cl^-. Studying the combination of waste use with carbon sequestration methods and computer models is a promising research direction that will accelerate the development and implementation of these materials.

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Soda production waste mainly consists of $CaCO_3$, which is a raw material for Portland cement production, and accounts for more than 80 wt.%. The authors of [23] investigated the chemical composition, physical properties, and hydration mechanism of Portland cement specimens obtained using waste with different Cl^- contents. The results showed that water scrubbing reduces the Cl^- content to 0.26 wt.%. It has been established that Portland cement with a solid waste content of 25.64 wt.% meets the standard requirements for CEM I 52.5N cement in terms of flexural and compressive strength. The permeability coefficient increased from $186.27 \cdot 10^{-13}$ to $8.65 \cdot 10^{-13}$ m/s, and the mass and compressive strength losses decreased to 6.53 and 7.33 %, respectively. It has been proven that the use of solid soda production waste as a limestone substitute is beneficial for reducing waste volumes and reducing limestone extraction.

Paper [24] examined the possibility of using soda production waste to produce clinker-free concrete by mixing it with metallurgical slags. Such a building material can replace traditional concretes, thus reducing CO_2 emissions from clinker production. Ammonia-soda residue (ASR), ground granulated blast-furnace slag (GGBS), steel slag (SS), and gypsum formed during flue gas desulfurization (FGD) were used as cementitious materials, and iron ore tailings were used as aggregates. According to the test results, ASR can reduce concrete fluidity and shorten initial and final setting times. In addition, the compressive strength of clinker-free concrete with a cementitious material consisting of 6 % ASR, 62 % GGBS, 20 % SS, and 12 % FGD reached 36.29 and 66.31 MPa at 3 and 360 days, respectively, increasing by 32 and 27 % compared to the control specimen. Information on the heat of hydration and porosity of the obtained materials confirmed that ASR accelerates the hydration reaction of cementitious materials, reducing the volume of 20-50 nm pores in hardened pastes but increasing the volume of pores >50 nm. The Cl^- concentrations in concrete with 6 % ASR in the cementitious material were $2.69 \cdot 10^{-3}$ and $1.24 \cdot 10^{-3}$ g/g at 3 and 360 days, respectively. Concretes with an ASR content of less than 6 % are suitable for manufacturing reinforced concrete structures, as confirmed by reinforcement corrosion tests. An assessment of the hydration mechanisms and characteristics of cementitious materials based on ASR-GGBS-SS-FGD showed that chlorides and carbonates in ASR accelerated the hydration process. The conducted studies lay a foundation for applying multicomponent solid wastes.

Use of waste in road construction

Road construction is one of the most promising applications in terms of the volumes of disposal and use of soda production waste without additional treatment. The processing is relatively inexpensive and technically simple; however, the waste must have the necessary strength characteristics [25]. It has been proposed to use sludge without additional treatment as a substitute for clay in the manufacture of surfacing for unpaved roads. A comparison of the particle size distributions of the sludge and local clay showed that they are identical in their fine fractions. An analysis of the dependence of the density of sludge specimens on the proportion of fine particles showed that treatment has little effect on sludge density. A study of the effect of moisture content on specimen density established that maximum density is achieved at a moisture content of ~19 %, which corresponds to the natural moisture content of soda sludge. It was found that the use of the polymer stabilizer M_{10+50} in an amount of ~0.08 wt.% increases the density of sludge specimens by a factor of ~1.4. A study of the effect of mineral composition on specimen strength showed that if the solid phase of the mixture consists of ~50 % soda sludge, ~25 % clay, and ~25 % crushed stone, then with the addition of 0.08 wt.% of the M_{10+50} stabilizer its strength reaches 11-12 MPa, which is comparable to the strength of M100/M150 grade concretes. The savings from the use of soda sludge in road construction can amount to about 2 million rub. per 1 km of road with a width of 8 m and a pavement thickness of 10 cm.

To assess the economic feasibility of using soda production waste in road construction, paper [26] compared the costs of constructing road pavements for 1 km of road with a roadway width of 8 m and an applied pavement thickness of 10 cm using conventional and proposed technologies. A comparative analysis of road construction estimates showed that the use of waste yields savings

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of about 2 million rub. per kilometer of route at current prices. Moreover, the main savings come from the materials used in construction. An equally significant effect is the slower filling rate of sludge storage ponds. The use of soda production waste in road construction is technically feasible and economically beneficial. Its use in surfacing for unpaved roads will not only optimize the consumption of natural resources but also reduce large technogenic formations in the Upper Kama region.

Soda industry waste can be used as an insulating material in the creation of solid waste storage sites [27]. Mechanical dewatering of the initial waste not only solves the technological problem of its placement but also reduces its hazard class from 4 to 5. A lime-soda-residue-stabilized soil (LSRSS) was obtained by modifying clay with the addition of dewatered soda residue (SR) and a small amount of lime for further stabilization. A comprehensive study was conducted, including laboratory testing of mechanical properties, investigation of the mechanism, and field verification to evaluate performance characteristics. The results of unconfined compressive strength (UCS), California bearing ratio (CBR), and resilient modulus (MR) determinations showed that with increasing SR content, the values of these indicators first increased and then decreased, reaching peak values of 0.62 MPa, 65.0 %, and 78.83 MPa, respectively, at an SR content of 30 %. The optimal ratio of components in LSRSS is 6 % lime, 30 % SR, and 70 % clay. The UCS, CBR, and MR values increased with increasing compaction degree and then decreased with increasing water content. The maximum values corresponded to 27 %, which is suitable for the application of LSRSS in subgrade. The results of field tests showed that the UCS, CBR, and MR values were 0.85 MPa, 86.5 %, and 135.7 MPa, respectively; the long-term performance characteristics of the road pavement were excellent. The results confirm excellent performance characteristics and lay a solid foundation for the widespread application of LSRSS subgrade.

Processing of waste into chemical compounds

Paper [28] proposes the use of a solution based on distiller waste as a coolant in a heat exchange system during soda production. The introduction of potassium dichromate into the system prevents pipe corrosion. A study of phase equilibria in the $CaCl_2 – K_2Cr_2O_7 – H_2O$ system made it possible to develop two coolant compositions:

- in the range from –7 to 50 °C: $K_2Cr_2O_7$ – 3; $CaCl_2$ – 10.2; H_2O – 86.8 %;
- in the range from 20 to 60 °C: $K_2Cr_2O_7$ – 6; $CaCl_2$ – 10; H_2O – 84 %.

A number of studies have demonstrated the feasibility of using distiller waste as a deicing material [29, 30].

A study by Chinese scientists showed the possibility of producing ultrafine calcium carbonate from distiller waste [31]. The product can be used as a filler in the rubber and paint industries.

Calcium and sodium hydroxide, as well as hydrochloric acid, can be obtained from distiller waste by evaporation [32, 33]. The process involves treating distiller waste with sodium hydroxide to precipitate insoluble calcium hydroxide. After separation of the precipitate, the filtrate, which mainly contains sodium chloride, is treated in a three-chamber membrane electrolyzer. This technological process can be organized without the use of additional chemical reagents.

A process has been developed for converting distiller waste into calcium peroxide (CaO_2), which is used in fish farming, poultry farming, agriculture, and other fields as a source of aeration [34-36]. The optimal process conditions have been established, making it possible to obtain a product with an active substance content of 87.29-88.13 wt.%.

A conversion process has been developed for producing calcium formate from sodium formate, calcium chloride, or calcium nitrate [37, 38]. Sodium formate is a byproduct of pentaerythritol production [39, 40]. The feasibility of using soda production waste (32 % calcium chloride solution, GOST 450-77 with Amendments N 1-3) has been proven. The maximum yield of calcium formate is

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77-79 %, with an active substance content of at least 99 %, which corresponds to the product offered on the market (TS 6-09-11-1149-78). Possible contamination of calcium formate with sodium chloride does not limit its use in the food and cosmetics industries. One of the advantages of the developed technological process is that the conversion method for producing salts is used in the production of potassium nitrate and dichromate.

The Table shows some methods for processing distiller waste into chemical compounds [5].

Methods for processing distiller waste into chemical compounds

Processing method	Advantages	Disadvantages
Production of anhydrous calcium peroxide	Production of calcium peroxide as a marketable product	Use of reagents: hydrogen peroxide and ammonia solution; generation of wastewater containing ammonium and sodium chlorides
Production of calcium chloride	Production of calcium chloride as a marketable product	Multi-stage production; complex technological equipment; high energy consumption
Production of calcium hydroxide, sodium hydroxide, and chlorine	Simpler processing method; reduced energy consumption; production of calcium hydroxide, sodium hydroxide, and chlorine as marketable products; production of water purified of calcium and sodium chloride	Complex technological equipment
Production of calcium formate	Production of calcium formate as a marketable product. Process temperature 22±2 °C; use of initial salts in crystalline or dissolved form	Utilization of the mother liquor after separation of the target product

Use of waste for soil reclamation

One of the promising methods for protecting and cleaning natural objects from contamination is the use of geochemical barriers. Geochemical barriers are sections of the Earth's crust in which, over a short distance, there is a sharp decrease in the intensity of migration of chemical elements and, consequently, in their concentrations [41]. In nature, processes occur that lead to the sealing of porous rocks, fractures, and joints of soil formations, making it possible to stop the inflow of brines into mines or to isolate particularly contaminated areas. Crystallization or precipitation plays a major role in these processes. The formation of calcium carbonate and sulfate (gypsum) and barium sulfate in many cases leads to a complete halt in the inflow of water and brine. The studies conducted prove that the imitation of natural processes can be successfully used in solving environmental problems [42].

Patent [43] proposes two compositions for reducing the water permeability of rocks, comprising a structure former agent (an aqueous solution of calcium chloride) and a precipitant (an aqueous solution of sodium sulfate plus additives). Soda production waste from Berezniki Soda Works JSC was used as the source of calcium chloride. The method of plugging water-permeable sections or zones in salt rocks includes opening zones of increased water permeability with plugging wells, preparing salt solutions at the surface, heating them if necessary, and injecting them into the plugging zone. In the first variant, the salt solutions are injected in two stages: the precipitant is injected first, and the structure former agent second. In the second variant, equal volumes of the structure former agent and precipitant solutions are mixed and injected in a single stage. The technical result is an expanded arsenal of plugging agents and improved reliability and quality of plugging of zones of increased water permeability in rocks.

Soil reclamation with soda production waste to restore fertility and improve the properties of contaminated or disturbed soils includes a technical stage (land preparation and waste application) and a biological stage (planting vegetation to restore plant cover). Soda production sludge contains compounds that can act as lime ameliorants and fertilizers, improving soil structure and increasing its

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fertility. This approach helps improve soil condition and eliminate the consequences of its contamination. The application of waste makes it possible to return land to a state suitable for agricultural use and to reduce reclamation costs.

Field experiments have confirmed that the application of sludge to soil normalizes the acidity of the medium and has a positive effect on the productivity of green plantings on saline soils [44]. When sludge and sewage sludge were used together in ratios of 1:2 and 1:1, a material was obtained that is characterized by new physicochemical properties and is suitable for biological reclamation [8].

Patent [45] proposes a material for the biological reclamation of disturbed lands, comprising soda production sludge of a fraction less than 0.5 mm, obtained by centrifuging aqueous extracts with a pH of 8.2-8.5, and dewatered activated sludge or its mixture with the sediment of primary settling tanks of municipal domestic wastewater, stabilized under natural conditions for 1 to 10 years, containing, wt.%: organic matter 49-67; mineral matter 33-51, including total nitrogen up to 5.7 and phosphorus up to 7.4. The mass ratio of sludge to activated sludge is 2:1-1:1.

The use of industrial waste, including soda production waste, is relevant for neutralizing acid mine drainage (AMD) and the consequences of its occurrence. The main causes of acid formation are the presence of sulfide minerals, an oxidizer (atmospheric oxygen and chemical sources), and water. Oil extraction, metallurgy, and tunnel construction are most often the cause of AMD [46, 47]. The development of deposits of minerals containing gold, copper, nickel, and other metals, as well as coal, is associated with acid drainage problems that can cause long-term deterioration of biogeocenoses, leading to reduced biodiversity and worsened human health [48] and the quality of agricultural products [49]. The environmental impact of AMD can be minimized by controlling the process of acid formation and its further migration, as well as by collecting and treating wastewater [50-52].

The most common method for neutralizing acid effluents is their treatment with limestone, slaked lime, soda ash and caustic soda, ammonia, calcium peroxide, kiln dust, and fly ash [53-55]. Neutralizing agents raise the pH of the effluents, accelerate the oxidation of the Fe^{2+} ion, and ensure the precipitation of hydroxides and carbonates of many metals [50, 56], which prevents further migration. The formation of a buffer solution when limestone is used makes it difficult to raise the pH above 6. It is ineffective in water with a high content of the Fe^{2+} ion, and the application process is more complex than when lime is used.

Acid mine drainage is the cause of the formation of technogenic soils, which are characterized by an acidic reaction of the medium and an elevated content of sulfates and trace elements in the surface layer [57-59]. Reclamation of technogenic acid soils is possible using passive or active methods, including the use of soda production waste [60]. It has been established that compliance with application dosages does not have a negative effect on agricultural products.

Soda production waste is used for soil reclamation in Korea [61]. Lime cake and calcite are applied in layers between coal waste and the topsoil, or mixed with the topsoil and coal waste. Treatment with lime cake raised the pH of the coal waste from 3.5 to 6 and that of the coal waste filtrate from 4.3 to 6.7. The increase in pH made it possible to ensure seed germination on the disturbed area.

The use of soda production sludge as a biological additive for the reclamation of disturbed lands has been successfully implemented in the Kizel Coal Basin (Perm Krai) [62, 63]. Sludge was applied at 10-40 kg/m^2; after plowing, 4-5 kg/m^2 of activated sludge from the treatment facilities of a chemical plant was applied, followed by sowing of plant seeds. The sludge composition comprised, wt.%: calcite 79-97, aragonite 1-2, dolomite up to 1, quartz 1-8, with water as the remainder. The activated sludge composition comprised, wt.%: mineral matter 53-78, organic matter 22-47, including total nitrogen up to 3.6 and phosphorus up to 4.8. Reed canary grass, red clover, alfalfa, and quackgrass were used for sowing.

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Papers [64, 65] present data on the soil properties at an acid mine drainage runoff site reclaimed about 20 years ago. At present, a stable plant community has been found at the site, represented by young birches (genus *Betula*), willows (genus *Salix*), and alders (genus *Alnus*), as well as herbaceous plants of the families *Cyperaceae* (genus *Carex*), *Poaceae*, *Onagraceae*, and *Caryophyllaceae*, and mosses. The soil has a pH of 5.3-4.4 and an organic carbon content of up to 19 % in the top layer (10 cm). In the unreclaimed soil, organic carbon is 8 % and the pH is 3.0. The formation of a stable plant community at the reclaimed site indicates the effectiveness of the method used. The measures taken made it possible to create a stable plant cover on disturbed lands, neutralize their toxicity, and dispose of chemical production waste. Economic calculations have shown that the secondary use of waste substantially reduces the cost of performing restoration work.

The authors' own studies conducted in the summer of 2025 showed the effectiveness of using an ameliorant based on soda production waste on the soils of reclaimed dumps of the Kizel Coal Basin. The dump soils are clayey, without a humus horizon, low-fertility, and acidic; the amount of NPK indicates a low supply of nutrients, and vegetation is absent or developed fragmentarily [66]. The application of soda ameliorant to the dump soils contributed to a decrease in acidity and an increase in the amount of calcium and the activity of enzymes (catalase, invertase) relative to the background plot.

Paper [67] presents the results of using soda production waste as a chemical ameliorant on slightly acidic soils. It was established that the application of lime ameliorant contributed to a decrease in the hydrolytic acidity of slightly acidic sod-podzolic soil by 1.4-1.7 mg-eq/100 g. This ensured an increase in the yield of barley and potatoes by more than 20 %. It has been proven that the use of the ameliorant reduces soil acidity more effectively than standard lime reagents.

The use of soda production waste has shown its effectiveness as an ameliorant for soils of mining landscapes. However, their use in agriculture must be preceded by determining chemical and toxicological characteristics, as well as selecting the application dose depending on the content of the main components.

Paper [68] presents the results of developing a substrate from soda residue and manganese production waste (SRMn) and evaluates its effectiveness for treating wastewater from freshwater fish farms in a constructed wetland (SRMn-CW). The main focus is on the problem of removing tetracycline (TC) and total phosphorus (TP), as well as the effect of the substrate on a number of factors and the dynamics of the microbial community. SRMn-CW effectively provided simultaneous and stable removal of TC and TP with efficiencies of 80.27 and 91.12 %, respectively. Even at high pollutant concentrations and varying pH conditions, the removal efficiency of SRMn-CW was above 86.63 % for TP and 71.42 % for TC. The results obtained expand the applications of soda production waste for treating wastewater from freshwater aquaculture facilities.

Constructed wetlands (CW) are promising facilities for treating acid mine drainage [69]. The extreme acidity and high concentration of heavy metals in AMD can lead to the destruction of CW without their preliminary treatment. To improve the CW substrate, composites of attapulgite and soda residue (ASR) were used. Compared with gravel-filled CW (CW-G), the removal efficiency of sulfates and Fe, Mn, Cu, Zn, Cd, and Pb in CW filled with ASR composites (CW-ASR) increased by 30 and 10-70 %, respectively. Metals were retained in the substrate in the form of carbonates, Fe/Mn (oxides) hydroxides, and sulfides. CW-ASR exhibited higher levels of photosynthetic pigments and antioxidant enzyme activity in plants, as well as a richer microbial community, than CW-G. The use of composites of attapulgite and soda residue mitigated the adverse effects of stress caused by AMD on wetland plants and microorganisms. In turn, the increase in the abundance of bacteria, especially sulfate-reducing genera (*Thermodesulfovibrionia* and *Desulfobacca*), contributed to the formation of metal sulfides, which allowed

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ASR to regenerate and capture heavy metals. The synergistic adsorption of ASR composites and microbial sulfate reduction maintained the stable and efficient operation of CW. Thus, the feasibility of using industrial waste and creating new low-cost and passive treatment systems has been confirmed.

Integrated waste processing

Paper [70] presents a review of the properties of soda production waste, including its hazards, its use in environmental management (wastewater treatment, flue gas desulfurization, and soil reclamation), and the associated risks. The limitations of "waste-to-waste" technologies are analyzed. Based on this analysis, the development of integrated technologies is proposed, including the safe disposal and recovery of resources from metal-laden sludge, effective dechlorination and use of sludge for reclamation of contaminated soil, pollution control through environmentally friendly processing methods, and long-term risk assessment.

Paper [71] examines the potential advantages, limitations, and prospects of technologies for processing soda production waste. The innovative technology is aimed at separating, purifying, and reusing solid, liquid, and gaseous byproducts, providing a more sustainable and cost-effective approach. The implementation of this technology can significantly reduce the environmental impact of soda ash production while promoting the development of a circular economy. However, high initial costs and technical barriers to integration continue to pose challenges.

The results of pilot tests demonstrate the potential of the technology to reduce waste generation, recover valuable resources, and minimize harmful emissions while improving the economic efficiency of soda ash production. Key achievements of the technology include:

- reduction of total industrial waste by 70 %;
- effective processing of solid, liquid, and gaseous byproducts;
- a high level of resource recovery, especially calcium oxide, ammonia, and sodium bicarbonate;
- reduction of water consumption by 60 % through effective treatment;
- reduction of energy consumption by 25 %.

For the processing of solid waste, processes such as pyrolysis, thermal decomposition, and chemical neutralization were considered. For wastewater treatment, a combination of filtration, neutralization, and ion exchange methods was used. For the capture and neutralization of harmful gaseous emissions, modern scrubbers and catalytic converters were used. The developed system makes it possible to recover valuable resources such as ammonia, sodium bicarbonate, and calcium carbonate.

Paper [72] examines the evolution of soda ash production methods. The environmental and economic problems of traditional methods are analyzed, including high energy consumption, environmental pollution, and waste generation. Promising alternatives are considered, such as modified Solvay methods using external CO_2 sources and a promising new production method using microorganisms. Methods for reusing waste (CaO, hydroxides, and CO_2) are shown in detail, although hydrochloric acid may be formed as a byproduct. The main focus is on the potential of innovative methods based on physical and biological processes to improve efficiency, reduce environmental impact, and lower energy and resource consumption.

Paper [73] evaluates six electrochemically-based alternatives to the Solvay process, with emphasis on their energy efficiency and economic feasibility. The processes include a stage of NaOH production by chlor-alkali electrolysis or electrodialysis with bipolar membranes, a concentration stage with mechanical vapor compression, carbonation of NaOH with CO_2 in a bubble column, crystallization of $NaHCO_3$ or $Na_2CO_3 \cdot H_2O$, and calcination of the salts to Na_2CO_3. The results indicate a reduction in energy consumption of 14-45 % for the five configurations studied compared to the traditional process. It was established that electricity can replace fossil fuels as the

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main source for soda production. With a 25-year service life of a plant with a capacity of 1000 t Na_2CO_3 per day, electrolysis-based processes demonstrate economic efficiency at net production costs of 0.31 to 0.37 euros/kg Na_2CO_3. Processes involving electrodialysis generally have significantly higher production costs. However, the analysis shows that economic efficiency can be achieved by reducing electricity costs and valorizing the low-concentration byproduct, hydrochloric acid.

Paper [74] describes a highly efficient electrochemical method for processing distiller waste to produce $Ca(OH)_2$, NaOH, and HCl. A two-stage process is proposed. In the first stage, distiller waste is treated with alkali to produce $Ca(OH)_2$ and a filtrate containing NaCl. In the second stage, the filtrate is processed in a membrane electrolyzer to produce NaOH and HCl solutions. It is shown that the process of treating distiller waste with alkali must be carried out at a molar ratio of $CaCl_2$:NaOH equal to 1:1.25. Processing the filtrate in a membrane electrolyzer makes it possible to obtain NaOH with a concentration of up to 4320 g/l and HCl with a concentration of 148 g/l.

Currently, there are marketable products obtained by processing distiller waste that meet the requirements of state standards: an ameliorant for liming acidic and solonetzic soils (TS 6-18-37-85); complex mineral additives for balancing the nutritional rations of agricultural animals (TS 6-18-3-80) and poultry (TS 6-18-25-079); sand-lime brick based on belite binder; technical calcium chloride (GOST 450-77).

Conclusion

Worldwide, soda ash is produced predominantly by the ammonia-soda process. A major drawback of this method is the hazardous waste it generates. While this waste has numerous potential applications, its disposal remains a pressing challenge due to the scale of soda production, the resulting waste volumes, and the financial investment required for disposal methods. The development of processing methods is being driven by tightening environmental safety requirements and the high cost of maintaining settling ponds; the choice of method depends on the plant's location, production areas, energy capacity, and the company's financial condition.

Methods for reducing sludge toxicity, using waste in construction (including road construction), and processing it into chemical compounds are described in literature. Soil reclamation using sludge is a promising direction. However, almost every case involves certain limitations to implementing the developed solutions. For example, the presence of chloride ions, small particle size, the thixotropic properties of the material, and variability in sludge composition limit the use of sludge in building materials. Road construction is the most promising avenue in terms of the volumes of waste disposed of without additional treatment. Land reclamation using this waste requires a selective approach to site selection and additional research. As publications show, soda production waste is a valuable raw material for restoring damaged lands and improving the fertility and resilience of soils, including agricultural soils. At the same time, it is important to consider its chemical characteristics and select optimal dosages.

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