Installation Project For Water Purification From Suspended Particles

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Currently, the issue of recycling coal waste becomes quite relevant all over the world, which is associated with tightening environmental standards and increasing production rates in the coal industry. So, to reduce the environmental load of effective coal waste management, innovative developments and implementation are required, aimed at processing, purification and disposal. The aim of this work is to evaluate methods for treating water containing suspended coal dust and to develop a treatment plant design along with approaches for pilot testing. A design of the plant for purifying water with suspended coal dust particles, a diagram of the interaction of elements, feasible technological solutions and options for the operation of the plant are proposed. The implementation of the proposed installation in the ports that ship coal allows us to evaluate not only water purification processes, but also measures aimed at optimizing expended resources and reducing the negative impact on the environment. The research results and technical characteristics of the proposed plant are discussed in the context of its application and benefits to industrial enterprises in the field of coal transportation. The water installation project can serve as the basis for implementing environmentally sustainable solutions in the field of water treatment and increasing the economic efficiency of transporting coal by water in the Caspian area. The proposed water purification plant incurs significant operational costs. Fire hazards in closed systems and coal dust pollution are still issues, even with the plant's adaptable design.

Keywords: coal waste; mine water; ecology; water treatment facilities; coal; filtration

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1. Introduction

Now, due to limited supplies from the Russian Federation, the European Union is faced with the urgent issue of finding alternative sources of coal supplies, including the ones from the countries of the Caspian region. In particular, Kazakhstan has the potential to increase supplies towards the Eurozone. Thus, the country supplied 1.5 million tons of coal to the European Union in January-May 2023, which is twice as much as in 2022.

At the same time, Kazakhstan sent most of its coal to the EU by sea, and a third of supplies by rail. The country plans to increase coal exports, including through the railway; Kazakhstan is considering the project for the development of the Aktau port in the Caspian Sea, after which fuel supplies to the EU through Azerbaijan and Georgia could be expanded. The project seems all the more realistic considering that Kazakhstan intends to expand the capacity of the Trans-Caspian Route (TMTM/Middle Corridor). Meanwhile, Azerbaijan and Kazakhstan are working on seaports development. The Baku International Sea Trade Port also plans to implement a number of projects to increase transshipment of all types of cargo. Table 1 presents the data on the volume of coal transshipment in the Caspian Sea ports.

The technology for transshipment of export coal involves unloading it from gondola cars, cleaning from foreign objects, crushing, stacking and storing it in the territory of the terminal (usually in open storage areas), delivering it from the warehouse to the border area for loading

Table 1. Volumes of coal transshipment in seaports of the Caspian region, million

Years	2021	2022	2023
Bulk cargo handled, total	191,0	197,2	214,0
Of which, hard coal, coke	41,6	71,4	966,0
% of exported coal from total coal	98,8	98,6	98,6

into a specialized bulk carrier. Thus, when exporting coal is shipped, it is expected to be repeatedly transshipped, creating ecological problems for the environment of the region and, above all, for the Caspian Sea. A very significant drawback of coal transshipment technology is that dusty coal, during repeated transshipment, pollutes the territory and water area of the seaport. Environmental problems manifest themselves to the greatest extent when using a clamshell technology. Sometimes, this technology is called an open coal transfer technology. To protect the environment, the management of coal terminals with the grab technology located within city limits takes all possible measures to reduce pollution levels and improve the environmental situation. To limit the spread of coal dust to adjacent areas, protective enclosing walls, the height of which exceeds the height of the coal stacks, and dome structures covering the territory of the coal terminals are erected at transshipment complexes. To reduce dust formation, various types of dust suppression equipment are used. Coal reloading grabs are equipped with an irrigation system; to reduce the formation of coal dust, mobile dust suppression units with water and snow spray mode (water fog generators) are used. However, it is not possible to completely eliminate the formation of coal dust during the coal transshipment using this method; moreover, a part of the water mixed with coal dust will inevitably enter the port water area and pollute the Caspian Sea. Various methods can be used to minimize water pollution, such as the use of special treatment systems, improved coal loading and handling technologies, and strict environmental standards and regulations.

The closed transshipment method is now being actively promoted as an advanced method; conventionally this is understood as a dome or a large hangar that covers the entire port. However, this method of dust protection is questionable, since in the case of construction the risk of fire increases significantly, which is fraught with much greater environmental damage. There is already such experience in a world practice: for example, a fire broke out in the port of Ventspils (Latvia) during closed coal transshipment. Thus, water purification in the port water area using various technologies is more promising, one of which is presented and described in this article.

Today, one of the common methods of water purification is its settling in special ponds. The still water settling process usually results in slow purification and clarification, but often does not achieve the required purification standards [1–4].

The degree of water purification is determined in accordance with its intended purpose. In some cases, it is necessary to bring the water quality characteristics closer to drinking standards, while in other cases, for example, for its use in rock transportation, the quality requirements may be less stringent. Particularly high standards are set for the water used in dust suppression systems, since it must be free of suspended solids and the resulting aerosol mixtures must not be toxic [1, 3, 5, 6].

The purpose of the work is to analyze methods for treating water containing suspended coal dust particles and develop the design for a treatment plant, as well as the methods for pilot testing of various treatment technologies.

2. Research methodology

Methods for treating wastewater depend on its physical and chemical properties, technical features and climatic conditions. In most cases, the use of one purification method is not effective enough, therefore, in the technological scheme of water treatment, combinations of various methods are often used including mechanical, physical-chemical, chemical and others. This is the only way to achieve a high degree of purification. The choice of a specific treatment scheme should precede a technical and economic analysis of several alternatives, taking into account environmental protection and environmental assessment of the project [7, 8].

As a rule, to purify water from coal dust particles, mechanical, chemical, physical and biological methods are used, and these methods are usually combined [9–12]. Mechanical methods include: straining and filtration; settling and filtration; centrifugal filtration and sedimentation; combined methods. Chemical methods are: neutralization; oxidation and reduction. Biochemical methods are: aerobic; anaerobic. Physical and chemical methods: coagulation and flotation; electrochemical cleaning; sorption; hyperfiltration; ion exchange; extraction.

Straining and filtration are mechanical methods of separating mixtures based on differences in particle sizes. Straining is used to separate solids from liquids or other solids through a screen or perforated material, where large particles are retained, and liquid or small particles pass through holes [13]. Settling is the method based on the difference in density of the mixture components. When settling, the mixture is left to rest for a time, allowing the heavier particles or components to settle to the bottom of the vessel. The pure phase (liquid or gas) is then removed, leaving a sediment [14, 15].

Centrifugal filtration and sedimentation rely on the use of centrifugal forces to speed up the separation process. With centrifugal filtration, the mixture is placed in a centrifuge, where, under the influence of high rotation speeds, the components are separated. Heavy particles settle on the walls of the centrifuge, and the clean phase is separated and removed [16, 17].

Combination methods involve combining multiple mechanical separation methods to improve the efficiency and accuracy of the process. For example, you can combine straining with filtration to remove both large and small particles from the mixture. Alternatively, settling before filtration can be used to pre-clean the mixture from large sediments, which improves filtration performance. These combined methods are widely used in various industries where a high degree of mixture separation is required [18].

Neutralization is a chemical treatment method aimed at changing the pH or chemical composition of reagents to achieve a neutral or stable state. This process is often used to treat wastes that contain acids or alkalis by adding reagents that can neutralize the hazardous substances and make the waste safe for further processing or discharge [19].

Oxidation and reduction are chemical methods based on changing the oxidative state of the substance atoms. Oxidation involves the transfer of electrons from one substance to another, causing the oxidation state of one substance to increase, and the other to decrease. Reduction, on the other hand, involves the transfer of electrons by a substance with a low oxidation state, resulting in a decrease in the oxidation state of that substance [20]. Aerobic biochemical methods are based on the use of oxygen in the processes of decomposition of organic substances by microorganisms. Anaerobic biochemical methods, in contrast, occur in the absence of oxygen and involve the decomposition of organic matter by microorganisms to produce methane and carbon dioxide [21]. Coagulation and flotation are physical-chemical treatment methods used to remove suspended particles from a liquid. The coagulation process involves the addition of coagulants, which help small particles stick together into larger aggregates, making them easier to separate from the liquid. Flotation, on the other hand, relies on the use of gas bubbles, usually air, to attach to contaminant particles and lift them to the surface of a liquid, where they can be removed [22].

Electric-chemical cleaning is a method that involves using electric current to remove contaminants from a liquid or gas. This process may involve electrolysis, electric coagulation or electric flotation, where electric fields cause the contaminants to decompose or change their physical-chemical properties, facilitating their removal [23].

Sorption is a process in which pollutants are adsorbed onto the surface of a solid material called a sorbent [24]. Hyperfiltration is a filtration method based on the use of membranes that allow only certain particles or molecules to pass through. Hyperfiltration provides a high degree of liquids purification by selectively separating components based on their size or chemical properties.

Ion exchange is a process in which ions in a solution are replaced by ions in the sorbent. This method is used to remove ions from solutions and purify water of various contaminants, including metals and other ions [25]. Extraction is a method in which target components are transferred from one phase to another using special solvents or extractants.

At the next work stage, taking into account modern methods of water purification, technological diagrams of a pilot industrial water purification plant were developed; they are divided into 4 sections. Fig. 1 shows a part of the equipment of a wastewater treatment plant and conducting research at the experimental site of open-pit coal mining enterprises to test the following stages of purification: reagent treatment, sedimentation, pressure filtration, sludge treatment and dewatering, adsorption, membrane purification, reagent-free water disinfection to obtain purified water that meets the requirements for discharge into a fishery reservoir.

The installation is multi-sectional, the first section, source water is supplied using a submersible pump, passes through the hydrocyclone, which performs mechanical cleaning from impurities, then through a disk filter, water enters a container with an electric mixer, from where the pump, is supplied to the reagent processing unit.

At the stage of reagent treatment, suspended substances and, partially, heavy metals, which are in both colloidal and soluble forms, are removed from the source water. The first section of the proposed scheme provides the heating part of the source water flow ($10 - 20\%$ of the nominal

Fig. 1. Equipment of a mine water treatment plant installed in a block container

capacity). Water is heated in a flow through instantaneous electric water heater.

Into the pipeline of the heated part of the flow, with an injection pump, is dosed at 6% (based on Al_2O_3). In order to increase the time and area of water contact with the coagulant solution after the injection point, a static mixer is installed. The preparation of the coagulant working solution is carried out in a container with a stirrer.

Dosing of 1% sodium hydroxide solution is carried out by injection pump, into the stream in front of the tubular flocculator. After the injection point, a static mixer, is mounted on the pipeline. Preparation of the working solution of sodium hydroxide is carried out in a container with a stirrer. Dosing is carried out in proportion to the readings of the pH sensor.

The introduction of a 0.1% flocculant solution is carried out by a dosing pump into the flow before entering the settling tank. After the injection point, a static mixer, is mounted on the pipeline. Preparation of the flocculant working solution is carried out in a container with an electric mixer.

The water treated with reagents enters the thin-layer settling tank, where the final formation of sediment flocs, and their deposition occurs. Periodically, the formed sludge from the settling tank is pumped into the sludge collection, using pump. Wash water from the granular filter is also sent to the sediment collector. Filtrate (clarified water) after filter press, is sent to the source water container, and the dewatered sludge for disposal.

In the second section of the water purification installation diagram, where clarified water from the settling tank is collected in a storage tank, and then by the pump, is supplied to the granular filter. The granular filter uses a two-layer loading of hydroanthracite and quartz sand.

After the end of the working cycle, the granular filter is regenerated. Regeneration of the filter loading is carried out by backwashing with demineralized water using a pump. Provision is made for dividing the flow of contaminated wash water after the granular filter over time. The first portion of rinsing water $(1/3)$, which carries the bulk of contaminants, is sent to the sediment collector, pos. SC. The remaining part of the rinsing water $(2/3)$ is sent to the source water tank.

In the third section, in which water purified from mechanical impurities after a granular filter is supplied to the 1-st stage reverse osmosis unit. In the process of reverse osmosis, water is purified from dissolved salts, while the initial stream is divided into two parts: permeate (desalted water) and concentrate - a stream enriched with salts and contaminants.

Before reverse osmosis, 2% hydrochloric acid is dosed into the water using pump, to pH 6.0-7.0 and 0.5% inhibitor solution with pump. After the acid injection point, a static mixer, is installed. The preparation of a working solution of hydrochloric acid is carried out in a container. Dosing is carried out in proportion to the readings of the pH sensor. Preparation of the inhibitor working solution is carried out in a container.

The 1-st stage reverse osmosis installation, includes: - barrier filter, with a filtration rating of 5 microns for fine cleaning from suspended particles; - high-pressure centrifugal pump, to create the required operating pressure in membrane devices; - membrane devices, each of which houses one reverse osmosis membrane element.

The permeate of the 1st stage of reverse osmosis with a flow rate of 750 l/h enters the storage tank. The 1-st stage concentrate with a flow rate of 250 l/h enters the container, and further with pump, is supplied to the 2-nd stage of reverse osmosis for additional concentration (volume reduction). The 2-nd stage reverse osmosis installation, includes: - barrier filter, with a filtration rating of 5 microns for fine cleaning from suspended particles; - high-pressure centrifugal pump, to create the required operating pressure in membrane devices; - membrane devices, each of which houses one reverse osmosis membrane element.

Permeate of the 2-nd stage of reverse osmosis with a flow rate of 150 l/h enters the storage tank. The 2-nd stage concentrate with a flow rate of 100 l/h is sent to drain into the sewer. In the final fourth section, the 1% sodium hydroxide solution is dosed into the permeate flow of the 1-st stage of reverse osmosis in front of the storage tank, to adjust the pH to 6.0-8.0.

The desalted water from container, using pump, is supplied to the adsorber filter. Water is supplied through the lower fitting to the lower part of the adsorber housing, from where it rises upward in an ascending flow. Adsorbent granules are fed from the loading hopper through a paddle feeder. Purified water is collected in a ring receiver and removed from the adsorber through the upper pipe. Purified water from the installation passes through an ultraviolet sterilizer, where its final disinfection occurs.

3. Results

To ensure the operation of the installation, the following methods have been proposed for conducting pilot tests of various mine water treatment technologies by introducing various equipment of the installation through the shut-off valve system.

Option 1 of the presented technological scheme (reagent treatment, sedimentation, mechanical filtration and reverse osmosis desalination of water with sorption post-treatment (RT+ S + MF + RODW +SPT)) (Fig. 2) is the most universal, using many different technological methods and involves purification from suspended substances, petroleum products, all groups of heavy (non-ferrous) metals, nitrite and ammonium nitrogen. To remove them, multi-stage reagent treatment, clarification by settling in a tank, and mechanical cleaning on pressure filters with granular loading are used. In addition, the installation includes a two-stage reverse concentrate unit, which is designed to remove water-soluble salts and reduce the total salt content (chlorides, sulfates, sodium, potassium, calcium, alkalinity, nitrates). If these indicators are exceeded, in this case the use of a reverse osmosis unit is necessary. A two-stage concentrate scheme allows to minimize the volume of withdrawn concentrate and thereby reduce the cost of its disposal by transferring it to the third parties. For final purification from soluble organic compounds and heavy metals, post-treatment with adsorption filters is used.

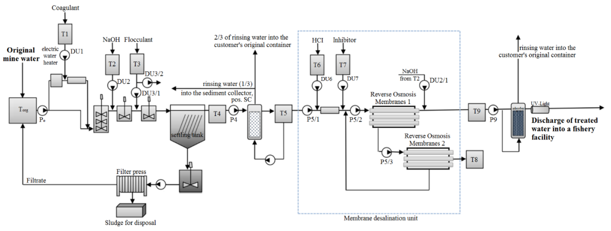

Fig. 2. A schematic flow diagram of a wastewater treatment plant according to the first option for organizing the operation of a pilot plant

The advantages of this scheme are the highest degree of purification in all aspects, including total salt content. The disadvantages are: operating costs are the highest compared to other technological schemes. When implementing this technology, two types of waste are generated. One of them is the solid waste of hazard class 4, which is a sediment after dewatering on a filter press (the sediment consists of colloids of coal dust, as well as a mixture of hydroxides and basic salts of heavy metals, the moisture content of the sediment is $70 \pm 5\%$). In addition, the polymer reverse osmosis membranes (once every 2-3 years) and adsorption loading (annually) are sent for recycling. All of the above wastes are hazard class 4. The second waste type is a highly mineralized concentrate, which is an aqueous solution of chloride - sulfate, sodium - calcium - magnesium salts with a total mineralization of up to 100,000 mg/l in an amount of no more than 10% (sometimes no more than 5%) from the initial purified water flow, which is usually hazard class 3. This concentrate can be processed thermally in an energy-saving evaporation plant or sent for disposal to specialized licensed organizations. Among the methods for recycling highly mineralized concentrate, the environmental legislation allows injection into ultra-deep underground wells (at least 1000 m deep). The disadvantage of all of the above disposal methods is the relatively high capital and operating costs. However, if the source water contains increased concentrations of mineral salts, and accordingly, the water treatment technological line contains a reverse osmosis stage, the issue of forming a reverse osmosis concentrate and its disposal cannot be avoided.

It should be noted that actual costs may be $30-50\%$ lower than those indicated due to the effect of scale operating on large flows of treated water. In this case, for example, the specific power consumption for high-pressure pumps for a flow of 100 m^3/hour in terms of 1 m^3 can be significantly lower than in a pilot plant with a capacity of 1.0 m^3/hour for source water. The same applies to reagents. When developing a treatment technology for an industrial flow, a multi-stage optimization of reagent consumption rates at a pilot plant is carried out, as a result of which the specific reagent consumption per 1 m^3 will be significantly reduced. This pattern applies to all 4 proposed technological schemes.

Option 2 of the presented technological scheme (reagent treatment, sedimentation, mechanical filtration and reverse osmosis desalination of water (RT+S+MF+RODW)) (Fig. 3) is similar to option 1, however, the adsorption purification stage is excluded in case when the concentration of petroleum products and heavy metals in the filtrate after reverse osmosis meets the requirements of the maximum permissible concentration for fishery facilities. Provided, of course, that the concentration of these impurities in the source waters are low, and the stages preceding adsorption purification guarantee the provision of the maximum permissible concentration for fisheries without its use. There will be no adsorption load saturated with heavy metals in solid waste sent for disposal. All other cleaning stages will work in the same way as described in option 1 with their advantages and disadvantages. Elimination of the adsorption stage allows reducing capital and operating costs in an industrial plant. However, this reduction is insignificant, less than 5%, and makes economic sense for purified flows of more than 300 – 500 m^3/ hour.

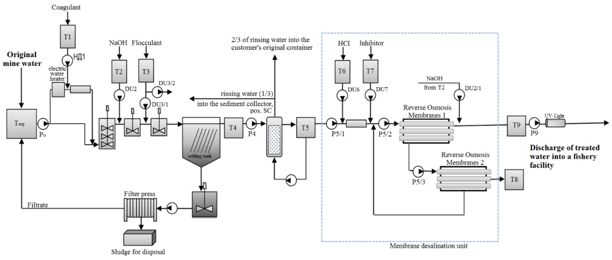

Fig. 3. The schematic flow diagram of a wastewater treatment plant according to the second option of the pilot plant operation

Option 3 of the presented technological scheme (reagent treatment, sedimentation, mechanical filtration and sorption post-treatment (RT+S+MF+SPT)) (Fig. 4) involves purification from suspended substances, petroleum products, all groups of heavy (non-ferrous) metals, nitrite nitrogen and ammonium. To remove them, in the same way as options 1-3, multi-stage reagent treatment, clarification by settling in a tank, and mechanical cleaning on pressure filters with granular loading are used. For final purification from soluble organic compounds and heavy metals, a post-treatment with adsorption filters is used. If the mineralization of mine water does not exceed MPC standards, then the use of reverse osmosis with its disadvantages does not make sense. The exclusion of reverse osmosis from water treatment technology will significantly reduce capital and operating costs for any volume of purified water, while the problem of concentrate disposal will not arise. All waste will be only solid, hazard class is 4. However, as noted above, the mineralization of mine waters should be less than 1,000 mg/l, other anions, such as sulfates, chlorides, nitrates should not exceed MPC standards. Economies of scale at capacities of 100 m^3/hour and above will reduce specific costs for water treatment by 25 – 30%.

Option 4 of the presented technological scheme (reagent treatment, sedimentation, mechanical filtration (RT+S+MF), involves purification only from suspended substances. Of course, this scheme will be characterized by minimal capital and operating costs, a minimal amount of non-toxic waste.

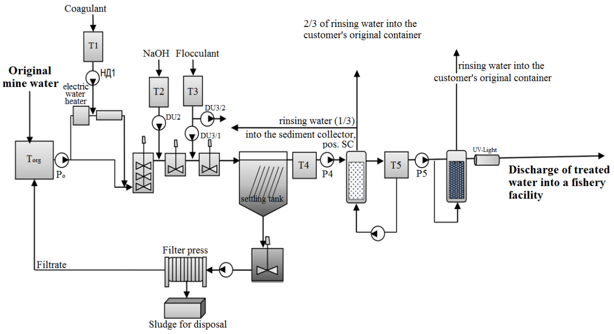

Fig. 4. The schematic flow diagram of a wastewater treatment plant according to the third option for organizing the operation of a pilot plant

4. Discussion

Our studies' results comprehensively evaluate the methods of treating water containing suspended coal dust and highlight the effectiveness of our proposed plans. This research project aligns with the current trends and practices in wastewater treatment in coal mining regions and industries.

Our study agrees with Dutta et al. [26], who highlighted the effectiveness of integrating physical/mechanical, chemical, and biological methods to achieve higher levels of wastewater purification. Ceretta et al. [27] concluded in their article that combining more than one treatment methodology is necessary to achieve better performance; this is consistent with our practice, where we utilized multi-stage reagent treatment, sedimentation, mechanical filtration, reverse osmosis, and adsorption filters [27]. One on the other hand, our study disagrees with the work of Sanghamitra et al. [28], whose model proposes a homogenous methodology involving only biological instruments.

Our study also highlighted the application of reverse osmosis in water treatment and wastewater desalination, making the water pure and safe to reintroduce into fisheries. Our findings agree with the case study of Simonič [29], who studied the application of reverse osmosis in purifying and reducing the content of sodium, aluminum, chloride, and nitrogen in wastewater. One of the major problems we faced in option 1 is the presence of reverse osmosis concentrates, which are deposited as solid waste; this problem corresponds with the study of Valdés et al. [30], who analyzed the physiochemical properties of the concentrates, their impact if not treated before disposing and the high cost of treating reverse osmosis sediments. Option 3 offers a sequence that aims to purify wastewater from coal mining regions and minimize cost as a solution to the high cost of the reverse osmosis process.

Post-treatment using adsorption filters removes heavy metals in options 1 and 3. The afforadability and regenerative ability of adsorption filter make them perfect when choosing an affordable regime for further purification after reverse osmosis. This data is supported by the review of Anderson et al. [31], who carried out an in-depth study on the treatment of heavy metal-containing wastewater using biodegradable adsorption filters. Option 2, on the contrary, downplays the effectiveness of adsorption filters and creates room for exclusion in a scenario where the impurities are low after reverse osmosis. This establishes reverse osmosis as a well developed wastewater treatment regime with high efficiency. This claim is supported by Zhang et al. [32], who highlighted the increased efficiency of wastewater treatment when using reverse osmosis. Option 4 offers a minimal, sustainable, and cost-effective treatment plan.

One of the benefits of our proposed options is their ability to fit into any environment and condition. This feature is highly essential and is supported by the work of Sturm et al. [33], who highlighted the importance of a wastewater treatment regime to adapt to the economic, environmental, and social parameters to foster sustainability.

The article presents several limitations. First, the operational costs of the proposed water purification plant are high, particularly due to the need for multi-stage processes like reverse osmosis. Second, fire hazards remain a concern in closed systems, which could negate some environmental benefits.

Further research is needed in order to find cost-effective ways for carrying out reverse osmosis processes and affordable disposal of reverse osmosis concentrates such as disk tube reverse osmosis as suggested by Zhang et al. [32] or integrating reverse osmosis with forward osmosis as suggested by the work of Patel et al. [34].

5. Conclusion

The paper presents the classification and analysis of the methods for treating water from suspended coal dust particles; some of the proposed methods have found application in the design of a water purification plant. The design of a water purification plant includes the technological diagram with the main technical elements, the diagram of their interaction, implemented technological solutions and plant operation options. The mobility and flexibility of the installation, with the ability to change the scheme and sequence of water purification, contribute to its adaptation to a variety of conditions and requirements.

The proposed water purification plant presents several promising perspectives. Its flexible design allows adaptation to various environmental and industrial conditions, making it suitable for different coal mining and transportation settings. The plant's multi-stage purification process, which integrates mechanical, chemical, and biological methods, ensures a high degree of water purification, potentially meeting stringent environmental regulations. This system can contribute to reducing pollution in key coal transshipment areas like the Caspian Sea, improving local ecosystems. Additionally, as coal exports continue to rise in regions such as Kazakhstan, the implementation of advanced water purification technology can enhance the sustainability of industrial processes, promoting environmental responsibility while optimizing resource use. Over time, economies of scale and technological advancements may further reduce operational costs, making it more feasible for broader application across various industries.

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