Group 10235

TANNITHEA

Anas Mamdouh
Ibrahim Walid
Mohab Abdelrahman
Mohamed Hassan

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Sand Filtration - Biochar - UV Disinfection

Abstract

Egypt's advancement is impeded by a multitude of grand challenges. This project tackles recycling garbage and waste for economic and environmental purposes; addressing and reducing pollution fouling our air, water, and soil; improving the uses of arid areas; managing and increasing the sources of clean water; and increasing the industrial and agricultural bases of Egypt. The purpose of the study is to utilize a combination of physical, chemical, and biological methods to treat tannery wastewater. The specific problem to be solved is water scarcity and improper wastewater disposal hindering land reclamation near the Rubiki Industrial Zone, Badr City. An automated water treatment system was constructed utilizing sand and gravel filtration, electrocoagulation, biochar adsorption, and UV disinfection. The prototype underwent targeted tests to ensure it met the design requirements, including reducing turbidity levels to below 50 NTU, maintaining pH within the range of 6.5 to 8.5, and adjusting salinity to fall between 450 and 1000 ppm for suitability in agricultural use. Some negative results were present but overcome through modifications. Major findings, after gathering the results, included a TDS removal efficiency of 81.54% and turbidity removal of 99.08%, demonstrating its ability to treat wastewater for land reclamation. Major conclusions confirm the prototype's effectiveness in overcoming the problem to be solved. Scaling the prototype could significantly contribute to solving Egypt's Grand Challenges.

Introduction

Egypt confronts significant grand challenges hindering its development. As of 2025, Egypt's population has reached 107,457,190, sharply increasing demand for water in a nation with only 560 m³ of renewable freshwater per capita annually, **as shown in Figure 1**, classifying it as water scarce. With this growing stress on water systems, only 31.7% of wastewater is adequately treated and reused, while the rest is discharged untreated into canals or open land. In industrial areas, improper wastewater disposal exacerbates pollution, contaminating nearby soil and water sources, which further harms agricultural potential. This pollution impacts land reclamation efforts, especially in arid regions where water is essential for restoring desert land for agriculture. The lack of effective wastewater treatment and water scarcity in these areas hinders the ability to reclaim land for sustainable use.

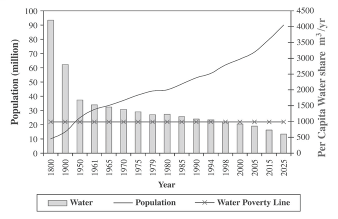

Figure 1: Population Growth and Per Capita Water Share in Egypt

Addressing these critical issues defines the problem to be solved, water scarcity and improper wastewater disposal hindering land reclamation near the Rubiki Industrial Zone, Badr City. Currently, it impedes sustainable development and contributes to ecological degradation in the region. If resolved, it would create a positive feedback loop, enhancing soil fertility, promoting sustainable practices, and increasing green spaces for better environmental health.

To broaden the perspective of the solution, prior solutions to similar problems were first reviewed, notably the El-Gabal El-Asfar and Bahr El-Baqar Wastewater Treatment Plants. El-Gabal El-Asfar in Cairo, with a 2.5 million cubic meters daily capacity, serves 12 million people and produces biogas. Bahr El-Baqar in Sinai, treating 1.4 million cubic meters daily, irrigates 168,000 hectares with high-quality filtration. Yet, El-Gabal El-Asfar faces high costs and sludge issues, while Bahr El-Baqar struggles with management complexity and sludge pollution risks.

Following a review of previous solutions, it was determined that the selected solution must fulfill specific design criteria—namely, lowering turbidity level to below 50 NTU, maintaining a pH between 6.5 and 8.5, and adjusting salinity under the threshold of 500 ppm to ensure the treated wastewater is appropriate for agricultural application.

The selected solution uses a multi-stage treatment system with sand and gravel filtration, biochar, electrocoagulation, and UV disinfection. Chosen for their simplicity, sustainability, and cost-effectiveness, the materials and steps **outlined in Table 1** were selected to meet the design requirements.

Materials & Methods

Table 1: Some of the materials used to construct the prototype.

Item Name	Quantity	Usage	Picture
3L plastic container	3	Used to construct the main container, filters, and EC system.	
3-6V water pump	1	Controlled water flow through the system.	
Arduino Uno	1	Served as microcontroller for sensors and pumps.	
TDS meter analog sensor V1.0	1	Measured total dissolved solids (TDS) in water.	
Turbidity sensor	1	Measured water turbidity levels.	
pH sensor	1	Detected water pH levels.	
DS18B20 waterproof temperature sensor	1	Measured water temperature for accurate TDS readings.	
Aluminum electrodes	8 11×6 cm	Used in electrocoagulation (EC) system.	
Biochar	0.25 kg	Enhanced biochar adsorption stage.	
Sand	0.5 kg	Formed sand/gravel filtration layer.	
Gravel	0.3	Served as distribution/drainage layers.	
UV lamp	1	Used in the disinfection stage.	

Methods

Prototype Construction

1. A 3D model was created in SketchUp to guide construction, **as shown in Figure 2**.
2. The base, **depicted in Figure 3**, was built using a 56 × 80 cm wood plank supported by nine 14 cm legs.
3. A sand/gravel filter was constructed using a plastic container with layers: top gravel (distribution), sand (filtration), and bottom gravel (drainage).
4. An electrocoagulation system was built using a plastic container and 8 aluminum electrodes, spaced 1 cm apart, and connected with crocodile wires, **as shown in Figure 4.**

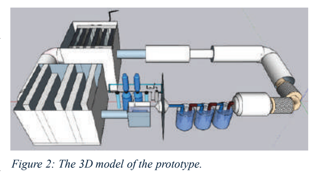
Figure 2: The 3D model of the prototype.

5. A UV sterilizer served as the biological disinfection stage.
6. A biochar adsorption stage was created using a plastic bottle with layers similar to the sand/gravel filter, but biochar replaced sand.
7. All stages were interconnected using pumps and hoses, **as shown in Figure 5**.

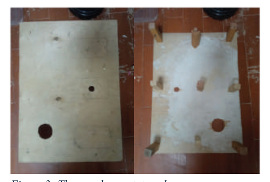
Figure 3: The wooden prototype base.

Automation & Monitoring System

1. pH, TDS, temperature, and turbidity sensors were installed in the main container, **as shown in Figure 6**, to monitor water quality parameters, connected to an Arduino Uno.
2. A water flow sensor was added between the biochar filter and the main container to track treatment cycles.
3. Pumps were programmed for specific operation times per cycle, with two controlling water flow to either enter or bypass the electrocoagulation (EC) stage.
4. An Android app was developed using Kotlin and Jetpack Compose for real-time monitoring and system control.
5. Sensor data was transmitted via Firebase to the app, which also sent control actions to the system through the same server.

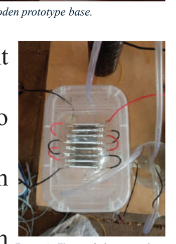
Figure 4: Wiring of electrocoagulation electrodes

Test Plan

A comprehensive set of tests was established to ensure the feasibility of the prototype to meet the design requirement:

1. The efficiency of the treatment processes was monitored over five complete treatment cycles for the same wastewater sample. Data on key parameters (e.g., pH, TDS, turbidity) were collected at each cycle. Linear regression analysis was applied to the results to determine the life expectancy of the treatment system.
2. The prototype's capacity was evaluated by measuring the volume of clean water produced every 10 minutes over a period of at least 1 hour. Additionally, the efficiency drop was monitored to assess system performance over time.
3. The system's energy consumption was calculated by measuring the electric current and voltage using voltage and current sensors. These measurements were taken during operation to determine the energy used per liter of clean water produced.

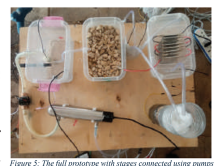
Figure 5: The full prototype with stages connected using pumps and hoses

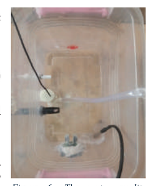
Figure 6: The water quality sensors placed in the main container.

Results

Negative Results

During prototype construction, fractures in the main container and sand filter caused water leakage, which were repaired using wax. The TDS sensor interfered with the pH and turbidity sensors, necessitating transistors to deactivate the TDS sensor during pH and turbidity readings. Biochar was not compacted enough at first, which caused water to flow too rapidly

Positive Results

Efficiency of Treatment Processes

The initial and final water quality parameters were measured for each cycle, and efficiencies were calculated, **as shown in Table 2**. The total TDS removal efficiency was 81.54%, turbidity removal reached 99.08%, and pH stabilized at 7.5. **Figure 7 shows** efficiency trends by number of cycle, while Figure 8 displays parameter readings across cycles. Applying linear regression analysis with an efficiency threshold of 30%, the life expectancy was estimated to be 276 cycles.

Capacity of the Prototype

The production rate of clean water was calculated to be 0.0814 liters per 10 minutes. The prototype could treat approximately 0.49 liters of water per hour under continuous operation.

Efficiency Drop

The efficiency drop was tracked by measuring water quality parameters and calculating the difference in turbidity and TDS removal efficiencies between consecutive cycles. The largest efficiency drops occurred during early cycles indicating rapid initial performance degradation. However, the rate of decline stabilized in later cycles, suggesting the system reached a steady operational state.

Energy Consumption

The system consumed a total of 245.9 kJ in 6.145 hours, equivalent to 81.9 kJ per liter of clean water. **Figure 9 illustrates** energy and power consumption across cycles.

Table 2: The initial values of quality parameters and final values after each cycle.

Cycle	Turbidity (NTU)	pH	TDS (ppm)	Temperature (°C)	Turbidity Efficiency (%)	TDS Efficiency (%)
Initial	656	7.43	2545	26.69	_	_
Cycle 1	127	7.8	1528.5	26.68	80.6	39.94
Cycle 2	49	7.6	1223.2	26.68	61.4	19.98
Cycle 3	28	7.5	979.8	26.71	42.9	19.9
Cycle 4	13	7.5	783.5	26.69	53.6	20.04
Cycle 5	6	7.5	469.7	26.70	53.8	40.05

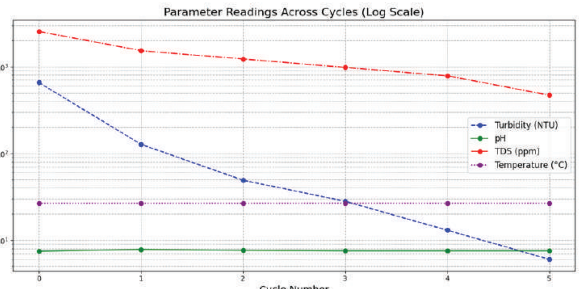

Figure 8: Parameter readings across treatment cycles.

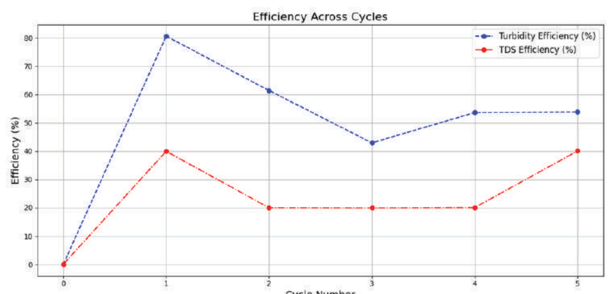

Figure 7: Efficiencies of the treatment system across cycles.

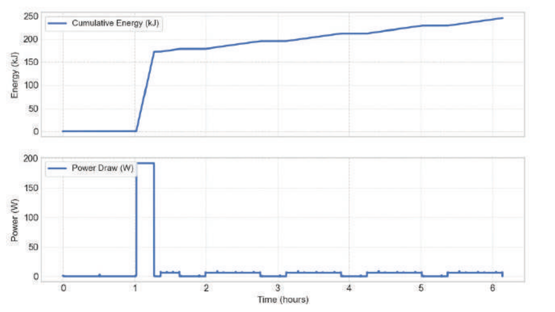

Figure 9: Power and energy consumption across treatment cycles.

Analysis

Purification Methods of Sand Filter

Sand filters remove contaminants via four primary mechanisms: physical straining, particle capture, electrostatic coagulation, and biological action.

Tannery wastewater usually contains excess leather trimmings which can block pumps if not removed. These trimmings are trapped in the pores between sand particles along with other relatively large substances using physical straining. The trimmings are specifically important as they contain collagen, which is a sticky substance that causes other particles smaller than the pores to adhere.

The second process consists of inertial impaction and adsorption (Maiyo et al., 2023, p. 2). Inertial impaction occurs when a flowing pollutant's inertia causes slight deviation from the water flow, leading to its collision and thus entrapment on the surface of sand particles. Molecules sometimes floc together due to van der Waal's forces leading to coagulants, which are then attracted and stuck to the surface of sand particles from adsorption. Adsorption can get very small particles too (Filtration & Gravity Filters, n.d.).

The third process depends on electrolytic charges. Colloids stay suspended in water as they have equal charge, so they continuously repel each other. As sand particles and flowing pollutants have opposite charges, they tend to attract each-other which then leads to their charges neutralizing. This breaks the "repel" chain and causes these pollutants to clump and coagulate (Indira Gandhi National Open University, 2017, p. 3).

The fourth process depends on biological methods. Flowing wastewater carries bacteria, viruses, and other organic substances through the sand filter. A large percentage of these organisms are deposited on the top of the sand filter, which leads to the formation of a suitable environment for bacterial colonies.

Electrocoagulation: Mechanism & Optimization

After the sand filter has removed the large and small particles in the wastewater, it still contains a large percentage of chromium and other dissolved metals. The next stage, electrocoagulation, aims to decrease this by coagulating such pollutants.

In electrocoagulation, an electrical current is passed between an aluminum anode and cathode immersed in the wastewater. At the anode, aluminum oxidizes to release Al^{3+} ions, while water is reduced at the cathode to generate hydroxide ions and hydrogen gas. The anode/cathode reactions are shown in the next equation:

$$\text{Anode: } Al \rightarrow Al^{3+} + 3e^- \qquad \text{Cathode: } 3H_2O + 3e^- \rightarrow \frac{3}{2}H_2 + 3OH^-$$

Several factors affect electrocoagulation. Firstly, electrode material. Aluminum was chosen due to its high efficiency in coagulating oils (Boinpally et al., 2023, p. 5) and the fact that it doesn't change the color nor taste of water unlike iron. Aluminum also leads to a lower increase in pH overall compared to mild steel. **As shown in Figure 10**, pH increased only by ~0.75 when using aluminum and by ~2 when using mild steel (Feng et al., 2007, p. 3).

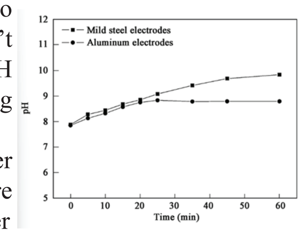

Figure 10: Comparison of pH increase from using aluminum electrodes and mild steel electrodes

Secondly, voltage and ampere. To get the optimal parameters for electrocoagulation, an engineer at Al-Rubiki's inactive treatment plant was asked. He stated that the voltage of 20 and an ampere of 7 is optimal. As we couldn't get a power supply fitting that exact description, we got a power supply with a 24 voltage and 10 ampere.

Thirdly, current density. Current density defines the number of ions being released into the solution. Increasing it means there'll be more ions to coagulate pollutants, but this is limited by the rate of coagulation of the ions and pollutants (Boinpally et al., 2023, p. 6). Since the total area of a single electrode is 110±2 cm², the area of the 8 electrodes used is 880±20 cm². Thus, the current density is:

$$J = \frac{I}{A} = \frac{8000\ miliamp}{880 \pm 20\ cm^2} = 9.1 \pm 0.2 \frac{mA}{cm^2}$$

According to literature, the optimal current density is 10 mA/cm² (Touahria et al., 2016, p. 1).

Lastly, the distance between each anode and cathode was found to be optimal at 1 cm (Hussein et al., 2022, p. 12). Decreasing it causes the aluminum ions to collide degrading them, which decreases efficiency. Increasing it leads to the current facing higher resistance while traveling from the anode to the cathode, and thus lower efficiency.

Biochar Adsorption

The slow-gravity sand filter followed by the electrocoagulation removes virtually all suspended solids and colloids but leaves behind low-concentrations of chromium and industrial dyes. Industrial dyes and chromium are both toxic to plants and animals, thus it's important to also remove them.

As none of the previous stages focus on removing color, where dyes make up 30% of total tannery discharge, it's important that this stage can get rid of colorization efficiently. The high porosity of biochar makes it perfect for removing colors. Papers have shown that it can remove up to 95% of dyes (Haddad et al., 2022, p. 2,3).

Biochar captures chromium through diffusion into pores, electrostatic attraction and hydrogen bonding. Biochar also reduces Cr(VI) into the less harmful Cr(III) using the reductive groups on its surface using ion exchange (Zhong et al., 2023, p. 2,3).

Additionally, literature has found that at lower chromium concentrations, biochar adsorbs better, at 98% efficiency, due to the less competition over binding sites. Therefore, its position at the end of the prototype design is very fit (where most of the chromium has already been removed from the EC). Biochar also gets rid of any precipitates or particles formed during the electrocoagulation stage using its small pores.

To optimize the filter, several measures were taken. Firstly, the biochar filter was wrapped in aluminum foil to prevent light penetration and thus algae growth (Biochar and Activated Carbon Filters for Greywater Treatment – Comparison of Organic Matter and Nutrients Removal, 2012, p. 11). Secondly, a separator was used between layers to decrease their mixing. Lastly, the biochar was grinded until it consisted of small rough particles, and all powder was removed.

UV Disinfection

Traditional water treatment systems utilize chemicals such as chlorine to kill bacteria. Although, as it is expected that the treated wastewater will be used for planting, using chlorine is inaccessible as it's poisonous to plants. Thus, using UV treatment instead is essential.

Chemical disinfectants decrease microorganisms by destroying their cellular structures. This leads to the cell's death due to its inability to metabolize. On the other hand, UV treatment damages nucleic acid which hinders the microorganism's capability to reproduce.

Nucleic acid consists of two components: purines and pyrimidines. UV, on average, causes more damage to pyrimidines. The damage comes in 3 main forms. Pyrimidine dimers form due to the presence of covalent bonds between adjacent pyrimidines. Photoproducts are similar to dimers. Protein-DNA cross-links are covalent bonds between proteins and DNA strands.

By positioning the UV unit as the final treatment step after both sand and biochar filtration have removed virtually all large and fine particulates and centering the lamp inside its holding tube, called the quartz sleeve, so that water flows evenly around it, we ensure that UV light isn't blocked by debris and that every microorganism passes within close, uniform distance of the lamp. This maximizes disinfection efficiency as UV intensity decays with distance (Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule, 2006, p. 44, 46).

Effective Particle Size

Effective particle size, or D_n, is used to measure the amount of a sample that would pass through a sieve of diameter D_n. That is, D_{10} is the maximum diameter length of the smallest 10% particles of a sample by weight. This parameter is used in sand and biochar filters to calculate the uniformity coefficient, which tells us how close the sizes of the particles are.

As calculating D_n requires unavailable equipment, an approximation was calculated. It's assumed that all sand particles have the same weight, thus D_n would be referring to the n% of particles with a diameter less than or equal to D_n.

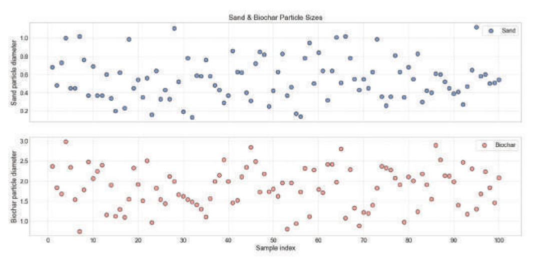

Figure11: Size datasets of both sand and biochar

The coefficient of uniformity is calculated by the following equation:

$$C_u = \frac{D_{60}}{D_{10}}$$

To calculate D_{60} and D_{10}, two samples of 100 grains of biochar and sand were obtained from the filters. Then, a digital vernier caliber was used to measure each grain's largest diameter to obtain 2 datasets, **shown in Figure 11**.

These values were inputted into Excel and, using the PERCENTILE.EXC function, their 10th and 60th percentiles were computed. In the case of the sand particles, $D_{S60} = 0.596$ and $D_{S10} = 0.272$. In the case of the biochar, $D_{B60} = 1.99$ and $D_{B10} = 1.111$. Thus,

$$C_S = \frac{D_{S60}}{D_{S10}} = 2.191,\ C_B = \frac{D_{B60}}{D_{B10}} = 1.791$$

Literature has found that for all granular media filters (such as slow sand filters and biochar filters), C should optimally be in the range between 1.5 to 2.5 (Centre for Affordable Water and Sanitation Technology (CAWST), 2009, p. 98).

Learning Outcomes Table

L.O	Concepts	Connection
CH.2.08	Electrolysis, Factors affecting the types of liberated substance	Electrolysis of water was applied in electrocoagulation, using four adjacent aluminum electrolytic cells to remove heavy metals and contaminants.
PH.2.08	Electromagnetic induction	Electromagnetic induction was utilized in relays to control water pumps via electric signals.
PH.2.16	Bipolar Transistor (PNP) and (NPN), Use of the transistor as a digital switch	PNP and NPN transistors were used as digital switches to activate/deactivate the TDS sensor, preventing interference with other sensors and improving accuracy.
CS.2.05	Mobile App Structure, Android Studio	An Android app, developed using Kotlin and Android Studio, was created to monitor and control the water treatment system.
MA.2.10	Percentiles	The concept was used to distribute the datasets containing the diameters of sand particles and biochar into ranked percentiles.
BI.2.09	Hormonal Control of Cycles, Feedback Systems	A feedback system was implemented in the prototype to ensure treated water meets the defined design thresholds.

Conclusions

To sum up, the selected problem to be solved through this project was water scarcity and improper wastewater disposal hindering land reclamation near the Rubiki Industrial Zone, Badr City. The solution consisted of 4 physical and chemical treatment stages. Electrocoagulation, renowned for its high efficiency in removing contaminants that are challenging to address through filtration or chemical treatment, played a vital role in the prototype alongside sand filtration, biochar, and UV stages. Despite some negative results, the prototype successfully met all the design requirements, reducing salinity to 469.7 ppm, turbidity to 6 NTU, and maintaining the pH level at 7.5. Compared to prior solutions, like New Cairo and Bahr El-Baqar wastewater treatment plants, the project uses easily accessible and recycled materials for eco-friendly and more cost-effective results. By combining the strengths of earlier methods while addressing their limitations, this project delivers a practical and sustainable solution for reducing salinity, TDS, turbidity, and pH, offering significant potential for environmental sustainability.

Recommendation

Real-life Application

It's recommended that the project is implemented in the Rubiki Industrial Zone, **shown in Figure 12**, located in the Cairo-Suez district of northern Badr City due to its high levels of pollution. This zone includes an area known as The Leather City, which contains numerous tanneries. Once treated, the wastewater resulting from the treatment process will be redirected to irrigate non-fruit-bearing trees, which do not require high water purity. This approach not only addresses water pollution but also supports environmental improvement by helping reduce greenhouse gas emissions in the area.


Figure12 Al Rubiki Industrial Zone, Badr City.

Centrifugal Sludge Pump (Slurry Pump)

Using a centrifugal sludge pump is recommended at the bottom of the EC tank to remove the dense flocculated wastes during operation, **as shown in Figure 13**. During the operation of the pump, the impeller converts electric energy from the motor to rotational kinetic energy. This motion creates a low-pressure zone at the area where the sludge is accumulated. This allows the sludge to flow through the suction pipe to an external tank where the sludge is then taken and removed safely. The pump will be connected to the smart system of water treatment where a sensor will sense the sludge level. When the sludge level gets low the pump will be turned off automatically to avoid excess water flow through the pump. Sensors monitoring sludge levels can reduce unnecessary pump operation, saving up to 20–30% of energy costs associated with continuous pumping.

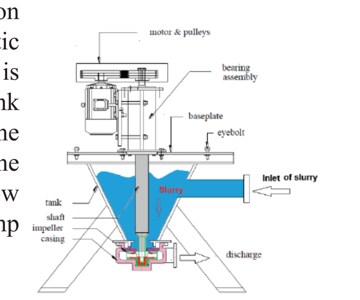

Figure13: Structure of a centrifugal sludge pump

Magnetic Biochar

In the water filtration system, we encourage using magnetic biochar instead of the normal biochar stage. Magnetic biochar is synthesized by incorporating transition metal nanoparticles, and their oxides, especially Fe_3O_4, into biochar. It enhances adsorption capacities and facilitates easy separation from treated water and thus decreasing the inorganic contaminates, such as heavy metals, and organic contaminants, like dyes, more efficiently. Magnetic biochar derived from woodchips has achieved a maximum Cr(VI) adsorption capacity of 80.96 mg/g (Santhosh et al., 2020), while the normal biochar has a capacity of 50 mg/g. In addition, the magnetic biochar maintained high removal efficiency over multiple cycles, which indicates its cost-effectiveness. The adsorption mechanism involves electrostatic attraction, then reduction of Cr(VI) to Cr(III), and complexation with functional groups on the biochar surface, where the surface of the biochar has functional groups, like -OH, -COOH, that can bind to Cr(III) to form complexes.

Sand rewashing

Sand rewashing is a process that restores the filtration capacity of sand by removing contaminants accumulated during use. There are three main ways of rewashing: backwashing, air scouring, and chemical treatment. Backwashing uses high-pressure water, while air scouring employs air to dislodge impurities. Chemical treatments help dissolve and remove organic and inorganic contaminants, especially heavy metals like chromium. To remove heavy metals, the alkaline method is preferred, which involves using chelating agents like EDTA or citric acid. Their combination restores up to 90% of the sand's original adsorption capacity. Rewashing reduces the need for new sand by up to 50% annually, leading to cost savings of 30-50%.

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