

Using Sawdust as a Sustainable Adsorbent for Removing Toxic Heavy Metals from Aqueous Solution

Yasir A. J. Alhamadani¹, Younus Mohammed Abed², Reem Wael Shahadha³, Ali Abed Salman⁴, Mohammed Nsaif Abbas⁴

¹Directorate of Construction and Building, Ministry of Higher Education and Scientific Research, Baghdad, Iraq

²Ministry of Education, General Directorate of Education in Baghdad Karkh III District, Baghdad, Iraq

³Department of Pharmacy, Al Hikma University College, Baghdad, Iraq

⁴Materials Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq

Abstract

Background: The Environmental Protection Agency (EPA) sets the maximum allowable dose for thallium in drinking water at 0.002 mg/L, and notes that chronic exposure leads to hair loss, kidney damage, and liver and heart disorders, depending on the severity and duration of exposure. This paper aimed to remove thallium ions from aqueous solutions using sawdust as a low-cost adsorbent.

Methods: White poplar wood sawdust was prepared and used as an adsorbent. The experiments were conducted in batch adsorption unit at different pH levels, contact times, agitation speeds, temperatures, initial concentrations, and doses of sawdust.

Results: The maximum thallium removal efficiency was 92.12% conducted at pH 6, contact time 150 min, agitation speed 450 rpm, thallium initial concentration 90 ppm, temperature 25 °C, and sawdust dosage 6 g. Morphological tests showed that thallium ions exploited almost all active sites of sawdust, and the surface area decreased by about 95% after adsorption. FT-IR and SEM tests confirmed that sawdust contains various functional groups such as -OH and -COOH responsible for the adsorption. The isothermal and kinetic results exhibited a better agreement with Langmuir and intra-particle diffusion models, respectively. Thermodynamically, the adsorption was of negative ΔS and ΔG values at all temperatures, while ΔH was -176 kJ/mol.

Conclusion: The study demonstrated that raw wood shavings can be used as an effective adsorbent to remove toxic thallium ions from contaminated aqueous solutions.

Keywords: Adsorption, Aqueous solution, Batch unit, Sawdust, Thallium

Citation: Alhamadani YAJ, Abed YM, Shahadha RW, Salman AA, Abbas MN. Using sawdust as a sustainable adsorbent for removing toxic heavy metals from aqueous solution. Environ Health Eng Manag 2026;13:1633. doi:10.34172/EHEM.1633

Article History:

Received: June 1, 2025

Revised: July 16, 2025

Accepted: August 18, 2025

ePublished: May 10, 2026

*Correspondence to:

Mohammed Nsaif Abbas,

Email: mohammed.nsaif.

abbas@uomustansiriyah.edu.iq

Introduction

Wastewater pollution is one of the biggest environmental challenges today, as it contains numerous hazardous pollutants, such as complex organic matters, toxic inorganic compounds, pathogens, drugs and pharmaceutical residues, excess nutrients that cause eutrophication, etc. (1). Heavy metals are among the most important pollutants that are constantly present in wastewater. They are considered among the most dangerous types due to their high capacity to accumulate within living organisms and their resistance to biological decomposition (2). Heavy metals are elements with high atomic numbers and densities five times the density of water or higher. They are not specified in a specific group of the periodic table and include iron, mercury, lead, nickel, cadmium, chromium, copper, antimony, tin, zinc, cobalt, silver, gold, platinum, titanium, vanadium,

thallium, etc. (3). These metals enter wastewater from a variety of sources, most notably industrial waste, such as metallurgy, electroplating, battery manufacturing, leather tanning, papermaking, and mining, to name a few (4). Agricultural runoff is an important source of heavy metals, as the use of pesticides and chemical fertilizers containing heavy metals causes pollution of surface and groundwater sources, in addition to irrigation water returning from agricultural lands (5). Another source is household waste through the disposal of some household products, medicines, or chemicals (6). This type of pollutant poses a direct threat to human health through bioaccumulation in the food chain, causing chronic diseases such as cancer, kidney failure, and neurotoxicity (7). Heavy metals also have widespread economic impacts resulting from increased water treatment costs and the deterioration of the agricultural and tourism sectors. they



also affect soil quality and crops and lead to ecological imbalance in aquatic systems (8). One of the most important heavy metals with widespread use in human life is thallium. It is used in the manufacture and production of infrared sensors, many portable x-ray units that require only continuous charging to operate, and most devices used to detect gamma rays (9). In addition, thallium is used in industry in the manufacture of electronic devices, electrical switches, closures, various optical materials, some special types of high-refractive index glass, and in glass coloring (10). Thallium is also used in the manufacture of watches, fireworks, some electrical wires and conductors, photography, and the production of moving images (11). Due to its unique properties, it has been used in the manufacture of special alloys, such as the mercury-thallium alloy, which is used in thermometers and low-temperature switches (12). However, this heavy metal, distinguished by its industrial efficiency and important uses, it is also distinguished by its various negative impacts on life and health (13). Soluble thallium salts (many of which are virtually tasteless) are highly toxic and can be easily absorbed through the skin, digestive tract, and lungs (14). Historically, thallium was primarily used in the manufacture of various poisons and antidotes, as well as in the production of numerous insecticides, such as rat and ant poison. However, the use of these products was banned in the United States in the 1970s due to safety concerns (15). When thallium enters the body, whether through inhalation, absorption through the skin, or ingestion, it quickly spreads to affect many vital systems, most notably the nervous system, liver, kidneys, heart, and skin (12). Acute symptoms usually appear 12 to 14 hours after exposure and include severe abdominal pain, vomiting, diarrhea, or constipation, followed in severe cases by neurological disturbances such as delirium, convulsions, coma, and death (16). Thallium also causes hair loss (alopecia areata), painful peripheral neuropathy, vision disturbances, and a characteristic skin rash. The severity of these effects increases with continued exposure or accumulation of the element in the body (17). The half lethal dose (LD₅₀) for thallium and its water-soluble compounds in humans is estimated to be 10 to 15 mg/kg body weight, with fatalities reported at lower doses (approximately 0.9 to 9.4 mg/kg), while the minimum lethal dose for adults ranges from 0.7 to 1.1 g. A study by Gupta (2012) indicated that a single dose of 15 mg of thallium/kg body weight is lethal in guinea pigs, dogs, and humans. The median lethal dose (LD₅₀) is 15 mg/kg in rats and 16–27 mg/kg in mice (18–20). The danger of thallium lies in its slow elimination from the body. Its biological half-life in humans is approximately 10 days and may reach 30 days, allowing it to accumulate and cause chronic poisoning, even with exposure to small amounts (12,21). As for other organisms, studies have shown that thallium causes growth and reproduction disorders and damage to vital organs and negatively impacts biodiversity in polluted environments (12,22). This has prompted several environmental agencies, such as the US Environmental

Protection Agency (EPA) and the World Health Organization (WHO), to classify it as an element highly hazardous to public health and the environment and to recommend minimizing exposure to it (23,24). The Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) have set the legal limit for workplace exposure to the toxic metal thallium at 0.1 milligrams per square meter of skin over an eight-hour exposure period (equivalent to a full workday) (25). Thallium exhibits high toxicity not only to humans but also to plant and animal organisms, negatively affecting their basic biological processes (22). In plants, thallium is similar to potassium, a vital element for growth and photosynthesis. This allows thallium to penetrate plant cells and replace potassium in metabolic processes (26). This disrupts enzyme function, reduces energy production, and damages plant tissues, resulting in slowed growth, reduced resistance to disease, and, in some cases, cell death (27). In animals, thallium causes severe neurological disorders, liver and kidney damage, and heart and blood disorders. It also affects reproduction and survival (14). It is considered toxic to aquatic organisms such as fish and invertebrates, as it leads to reduced survival and reproduction rates, thus affecting the ecological balance in aquatic systems (28). Environmental studies have shown that the accumulation of thallium in soil and water leads to food chain toxicity, threatening biodiversity and increasing the risk of toxins being transmitted to humans through food (29). Of course, these values vary depending on the form of thallium. Due to their high toxicity, thallium-containing compounds must be released into the environment within globally or locally mandated limits. Therefore, treating the pollution caused by this heavy element is an important priority for every industry it is used in (30). Currently, there are many methods and techniques used to treat water pollution with heavy metals, including reverse osmosis, nanofiltration, ion exchange, physical precipitation, chemical precipitation, electrodeposition, redox reactions, coagulation and flocculation, phytoremediation, bioremediation, biofiltration, thermal stabilization, incineration, electrochemical treatment, electrocoagulation, permeable reactive barriers (PRB), photocatalysis, evaporation, chelation, etc. (31). Although all the above methods have a reasonable efficiency in treating heavy elements, they have limitations and drawbacks that affect their use as a treatment method, including high cost, high energy consumption (32), the need for large spaces, pre-treatment requirements, the need for special equipment, or inefficacy in treating pollutants with extreme concentrations (33). However, the advantages of the adsorption method have rendered it a strong competitor against these methods. It is a simple technology that does not require preliminary preparations, and it can deal with all pollutants at extreme concentrations (34). It does not require large spaces, special equipment, or high costs; in addition, it has moderate energy consumption, which has attracted the interest of

researchers as a promising method in water treatment (35). The adsorption method has proven its efficiency in treating various types of pollutants such as dyes (36), organic materials (37), acids (38), inorganic toxins (39), pharmaceutical industry waste (40), pesticides (41), drugs (42), sulfurization component (43), water hardness (44), eutrophication elements (45), and various heavy metals (29), not only from polluted water, but also from contaminated soil (8) and crude oil (46). Despite these advantages and high treatment efficiency, expensive adsorption media have been a real obstacle to this method. Activated carbon (47), zeolite (48), alumina (49) and other well-known adsorption media require great effort and high cost to produce. This has prompted specialists to search for inexpensive and efficient alternatives, and they have found what they were looking for in agricultural and industrial waste, which provides a sustainable and inexpensive source of adsorption materials or raw materials for preparing other adsorption media (50). Rice husks (51), watermelon rinds (52), orange peels (53), banana peels (54), mandarin peels (55), eggshells (56), almond peels (57), lemon peels (58), sunflower husks (5), aluminum foil (59), pomegranate peels (60), algae (61), water hyacinth (62), tree leaves (63), spent tea leaves (64), and residual sludge (65) have been proven to be highly efficient in treating contaminated media at low cost compared to other adsorption media. Due to the quantities produced, they are considered available and non-valuable resources. On the other hand, this method is considered one of the economic methods for disposing of this waste (66). Although the accumulation of these wastes, which are often loaded with toxic substances, is a significant problem, the concept of zero residue level has opened up wide horizons for benefiting from these residues. They can be used as raw materials in the preparation of useful chemicals such as acetone (67) and promoted bioethanol (68), as catalysts (69), as additives to reinforce concrete mixtures (70), or as pesticides for rodents (71). They can also be converted into nanomaterials (72). From a review of the literature, it is noted that research papers dealing with the treatment of heavy metals constitute a large proportion of research specializing in environmental issues. Many researchers have studied the removal of thallium by adsorption using different media. Using titanate nanotubes and fabricated amorphous titanium dioxide, Liu et al., 2014, (73), and Zhang et al., 2022, (74) investigated the adsorption of Tl(I) and Tl(III), respectively, while Kam et al., 2022, (75) examined the ability of alumina nanoparticles to treat aqueous solutions contaminated by thallium under different operating conditions. Voegelin et al., 2022, (76) studied the adsorption of Tl(I) using mica and (micaceous) clay minerals. The purified illite clay collected near Le Puy-en-Velay, France was employed as an adsorbent medium to remove thallium by Wick et al., 2018 (77). Gadooa et al., 2025, (13) used tangerine peels to recover thallium ions from aqueous solutions. Despite its toxic effect, research on treating thallium-contaminated water by adsorption is

still limited. To address this apparent deficiency, the present study aimed to use sawdust as a low-cost adsorbent to recover thallium ions from contaminated aqueous solutions, to determine the optimum conditions that achieve the best removal efficiency, to study the isothermal, kinetic, and thermodynamic adsorption behavior, and to determine the morphological changes in sawdust as a result of treatment with solutions contaminated with thallium. Finally, we investigated the disposal of toxic residues in a useful, simple, and environmentally friendly way.

Materials and Methods

Adsorbent Medium (Sawdust)

The sawdust used in the present study was of the Russian origin (white poplar wood), and was collected from the remains of carpentry workshops in Baghdad as a by-product, as shown in Figure S1. A sieve analysis was performed on a sample of the collected sawdust with a mass of 250 g, as shown in Table 1 according to the method described in (Raja et al., 2023) (30). Sawdust passing through a 30-mesh sieve was used as an adsorbent, as it represented the largest proportion by weight of passed material. The sawdust was washed with an excess of tap water, and then rinsed with distilled water. The sawdust was then dried at a temperature of 58 °C until the weight was stable. Finally, the dried sawdust was stored in a suitable place, away from moisture.

Chemicals

Several essential chemicals were used in the present study. Hydrochloric acid (HCl) of 35–38% concentration was supplied by Thomas Baker Chemicals, India, and potassium hydroxide (KOH) (Assay: ≥85.00%) was obtained from HiMedia Laboratories, India. Thallium nitrate trihydrate ($Tl(NO_3)_3 \cdot 3H_2O$) of 95% purity was purchased from Alfa Aesar, USA, and the double-distilled water used in all the experiments was obtained from a distillation apparatus (GFL-2014, German). All the laboratory glassware used was supplied by Borosil Glass Works Ltd., India.

Table 1. Sieve analysis of sawdust used in the present study

#	Sieve size (µm)	Mesh No.	Weight of Passed amount (g)	Percentage (%)
1	6730	3	4.3	1.72
2	4760	4	7.6	3.04
3	4000	5	6.55	2.62
4	2000	10	14.425	5.77
5	1000	18	31.45	12.58
6	595	30	45.625	18.25
7	354	45	87.9	35.16
8	250	60	29.275	11.71
9	125	120	15.775	6.31
10	74	200	7.1	2.84
Σ	-	-	250	100%

Stock Solution

To prepare the stock solution of thallium ions at a concentration of 1000 ppm, 2.175 g of thallium nitrate ($\text{Tl}(\text{NO}_3)_3 \cdot 3\text{H}_2\text{O}$) was used. This quantity was dissolved in a suitable quantity of double-distilled water in a one-liter glass beaker using a magnetic stirrer at room temperature for half an hour. After ensuring complete dissolution, more distilled water was added until the final volume of the solution reached 1 liter (13).

Adsorption Unit

The ability of sawdust to remove thallium(III) ions from contaminated aqueous solutions was investigated by conducting adsorption experiments using a batch-type unit and at various operating pH conditions, agitation speeds, initial thallium ion concentrations, adsorbent dosages, contact times, and temperatures, which were 1–8, 100–500 rpm, 1–100 ppm, 0.5–6 g, 10–180 min, and 25–50 °C, respectively. The adsorption unit is a water bath shaker of type (SHKA7000-1CE 4304, Thermo Fisher Scientific). Using dilution, contaminated thallium solutions were prepared from the previously prepared stock solution at a concentration of 1000 ppm. The pH of the solution was adjusted using 0.1 N HCl and KOH solutions to adjust the acidity and base effect, respectively. After adjusting the shaking speed and temperature, the glass flasks containing 100 ml of aqueous solutions contaminated with a known concentration of thallium(III) and the specified mass of sawdust were placed in the adsorption unit and the experiment was started. At the end of the specified time period, the solution was carefully extracted and filtered first using filter paper (Whatman™ No.1 of 110 mm diameter) and then using filtration equipment (Filtering Kit 250 mL, vacuum pump with gauge, KT3003-3 Science Lab Supplies, UK). The clear solution was examined using AAS at 258 nm wavelength (78), to determine the concentration of thallium remaining after adsorption, from which the adsorption capacity and efficiency were determined via equations (1) and (2), respectively (79).

$$\%R = 100 \times \left(\frac{C_o - C_f}{C_o} \right) \quad (1)$$

$$q = \frac{V(C_o - C_f)}{m} \quad (2)$$

where %R is the removal efficiency of thallium metal, C_o is the initial concentration of thallium (ppm), C_f is the final concentration of thallium (ppm), q is the adsorption capacity of sawdust, expressed in (mg/g), V is the volume of the solution (L), and m is the mass of sawdust used in each experiment (g).

Results

Morphological Studies of Sawdust Used for Thallium Adsorption

BET surface area: The surface area of the sawdust was measured using the BET technique. The surface area was 22.3 m²/g before thallium ion adsorption, as shown

in Figure S2, which reflects the nature of sawdust as a porous structure with an active outer and inner surface. After the adsorption process, the surface area decreased significantly to 1.17 m²/g, reflecting the effect of the interaction between thallium ions and the surface of the sawdust.

FT-IR Analysis

The sawdust used in the experiment showed a distinct FTIR spectrum before and after adsorption of thallium ions, illustrating the changes that occurred as a result of the adsorption process, as seen in Figure S3. The blue spectrum represents the FTIR test of the sawdust before adsorption, while the spectrum represented by red color represents the FTIR test of sawdust after the adsorption of thallium. It is clear from Figure S3 that there are various differences between two spectra, indicating the interference of thallium ions with the different bonds and the reduction of vibrational energy as a result of the formation of new bonds due to the effect of adsorption.

SEM Test

Before thallium adsorption, the surface of the sawdust shows a distinct porous structure with relatively regular cavities and voids. These pores and voids represent the active sites on the surface, which serve as the places for adsorption as can be seen from Figure S4a, while Figure S4b shows the SEM test of sawdust after thallium adsorption, showing noticeable changes in the surface structure of the sawdust. The changes between the two Figures, S4a and S4b, indicate the success of the adsorption process, as the thallium ions have interacted with the active sites on the surface of the sawdust, which has led to a reduction in porosity and the covering of the surface with deposits.

Point of Zero Charge

The results of point of zero charge (pH_{pzc}) experiments of sawdust, shown in Figure S5, demonstrate a characteristic behavior that reflects the chemical and surface properties of this material. At low initial pH values (1–3), the ΔpH values exhibit a strongly negative charge, indicating significant proton adsorption by the surface. When the pH value increases beyond 4, the functional groups on the adsorbent media begin to lose protons through a deprotonation process. At very high initial pH levels (13–14), the surface charge becomes increasingly negative, reaching its maximum levels, which suggests a highly deprotonated and reactive surface

Effect of Acidity Change on Thallium Adsorption

According to the results obtained from the above zero charge point experiments, the effect of pH on the removal of thallium from aqueous solutions was studied within a pH range of 3–10. It is noted that the thallium removal efficiency increases slowly from 9.6 to 35.5 with the increase in pH from 3 to 6, respectively, after which, the adsorption efficiency increases sharply until it reaches 100% (Figure 1). These results demonstrate that the effect

of pH on the removal of thallium(III) ions using sawdust as an adsorbent reflects a complex interaction pattern between chemisorption and precipitation mechanisms.

Effect of agitation speed change on thallium adsorption

The results of the effect of agitation speed on the removal efficiency of thallium(III) ions using sawdust, which are represented in Figure 2, reflect a direct effect of dynamic factors on the adsorption process. At low speeds (100–300 rpm), the data show a significant increase in the removal ratio (%R), rising from 3.62% at 100 rpm to 41.23% at 300 rpm. With the increase in the agitation speed from 300 to 450 rpm, the removal efficiency continues to increase gradually, reaching 51.14% at 450 rpm, after which, no further increase is observed with increase in agitation speed.

Effect of Initial Concentration Change on Thallium Adsorption

The effect of initial concentration on the recovery efficiency of thallium from contaminated aqueous solutions using sawdust as an adsorbent was studied at room temperature with pH, agitation speed, adsorbent dose, and contact time held constant at 1, 450 rpm, 1 g, and 180 min, respectively. The results shown in Figure 3 reveal a complex interaction between the physical and chemical properties of the adsorbent concentration and the adsorption behavior. At low initial concentrations (1–20 ppm), the removal ratio was relatively high, reaching 51.14% at 1 ppm, and gradually decreased with increasing concentration. As

the initial thallium concentration increased from 30 to 100 ppm, the removal ratio decreased significantly from 35.31% to 16.40%. At initial concentrations of 90 ppm and above, the amount of adsorbed thallium ($C_{in} - C_{out}$) is observed to stabilize at about 16.40 ppm.

Effect of adsorbent dosage change on thallium adsorption

Figure 4 shows the results obtained from changing the amount of sawdust used as adsorption dose versus the removal efficiency of thallium ions (%R). Initially, when using a low amount of sawdust (0.5 g), the removal ratio (%R) was very low (9.21%). With the increase in the added dose of sawdust, a significant increase in the removal ratio was observed, reaching 92.12% with 6.5 g of the adsorbent. The results also show that there is a linear increase in thallium removal with increasing dosage up to 6 g of sawdust. After this point, it can be seen that the percentage of thallium removal reaches the highest level (92.12%) and does not change when the dose is increased to 6.5 g.

Effect of contact time change on thallium adsorption

The effect of contact time on the thallium recovery efficiency was investigated within the range of 10–180 min using sawdust as a low-cost adsorbent. The experiments were conducted at the optimum values of pH 6, agitation speed of 450 rpm, adsorption dose of 6 g of sawdust, and initial concentration of 90 ppm, at room temperature. The results obtained from the contact time variation experiments are represented in Figure 5,

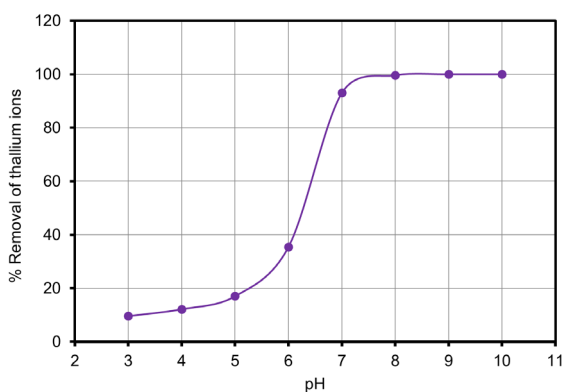


Figure 1. pH effect on thallium adsorption

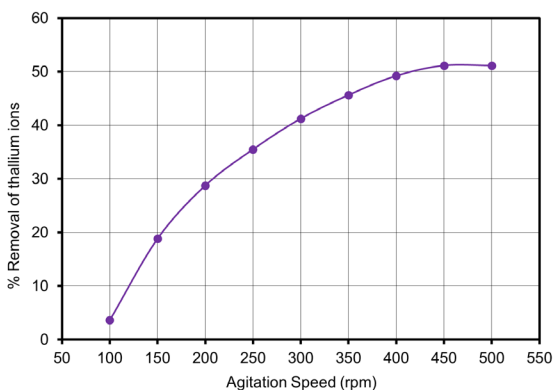


Figure 2. Shaking effect on thallium adsorption

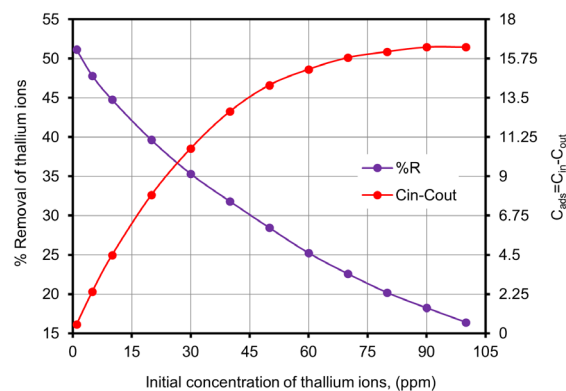


Figure 3. Initial concentration effect on thallium adsorption

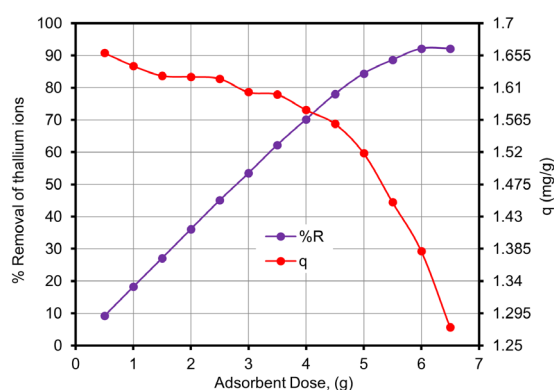


Figure 4. Adsorbent dose effect on thallium adsorption

which indicates that the removal efficiency of thallium ions by sawdust as an adsorbent gradually improves with increasing contact time, until it reaches the highest level of removal after 150 minutes of treatment. After 150 min, the removal ratio did not change, having reached its maximum value (92.12%).

Effect of temperature change on thallium adsorption

With the remaining operational parameters at optimum values, temperature experiments were conducted to determine the effect of temperature on the adsorption of thallium on the surface of sawdust as an adsorbent. Figure 6 shows the results obtained from the experiments on the effect of temperature on the removal of thallium ions using sawdust, which show a significant decrease in the removal rate with increasing temperature. The highest removal rate (92.12%) was recorded At 25 °C; this rate decreased to 4.04% at 50 °C. This change reflects the effect of temperature on the ability of the adsorbent (sawdust) to remove thallium.

Adsorption thermodynamic study

Thermodynamic studies in adsorption experiments are considered one of the basic studies to understand the nature of the adsorption process and determine whether the process is sustainable under certain conditions or not (80). These studies aim to analyze the energy changes that occur during the interaction of ions or molecules with the surface of the adsorbent, which contributes to determining whether the adsorption process proceeds spontaneously or requires the addition of external energy. In adsorption experiments, several thermodynamic variables are analyzed, including entropy change (ΔS), enthalpy change (ΔH), and free energy change (ΔG). These variables help in understanding the viability and stability of the adsorption process. Based on these results, the factors that affect the ability of the adsorbent to remove ions or molecules from solutions can be determined. The above variables are related to one another by a relationship called the Van't Hoff equation, which is represented by equation (3), from which the spontaneity of the reaction can be determined after calculating the equilibrium constant for the adsorption process at each temperature through equation (4):

$$\Delta G = \Delta H - T\Delta S \quad (3)$$

$$\ln k_d = -\frac{\Delta H}{R} \frac{1}{T} + \frac{\Delta S}{R} \quad (4)$$

where k_d is the adsorption equilibrium coefficient (-), R is the universal gas constant (8.3144 J/mol·K), T is the absolute temperature (K), ΔH is the enthalpy change (kJ/mol), ΔS is the entropy change (J/mol·K), and ΔG is the Gibbs free energy (kJ/mol).

The relationship between the equilibrium constant (k_d) and the free energy (ΔG) allows to determine whether the adsorption process is exothermic or endothermic in nature. By applying these equations in adsorption experiments, the thermodynamic efficiency of the adsorbent in removing target ions or molecules can be evaluated. The changes in enthalpy and entropy also help to determine the type of process (exothermic or endothermic) and the possible interaction between the adsorbent and the adsorbed molecules. The thermodynamic results obtained from the study, as shown in Table 2, indicate that the adsorption process using sawdust to remove thallium ions is an exothermic process, as evidenced by the negative enthalpy value ($\Delta H = -176.4163$ kJ/mol) at 25 °C. On the other hand, the negative entropy ($\Delta S = -522.05$ J/mol·K) reflects the reduction of randomness in the system during the adsorption process. This result is consistent with what was observed in the agitation speed experiments, where it was shown that increasing the speed improves the removal efficiency up to a certain point, leaving the system more

Table 2. Values of thermodynamic properties of thallium (III) adsorption

Temperature, (K)	ΔH (kJ/mol)	ΔS (J/mol·K)	ΔG (KJ/mol)
25			-20.7675
27.5			-19.4624
30			-18.1573
32.5			-16.8522
35	-176.4163	-522.0485	-15.547
37.5			-14.2419
40			-12.9368
42.5			-11.6317
45			-10.3265

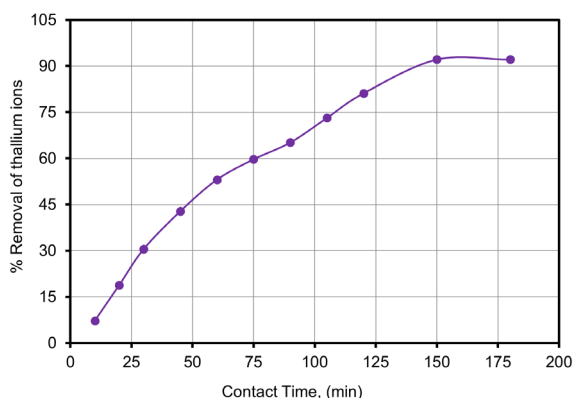


Figure 5. Contact time effect on thallium adsorption

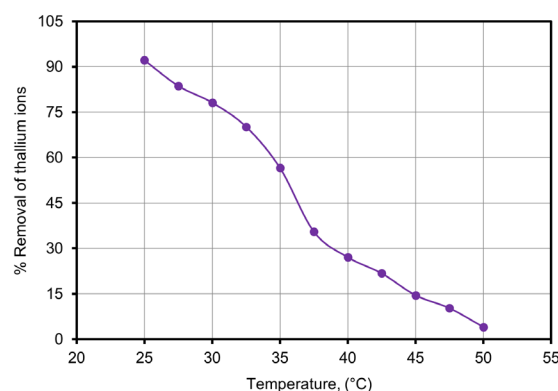


Figure 6. Temperature effect on thallium adsorption

ordered at better adsorption.

Adsorption isothermal study

The adsorption isothermal study is a study that aims to understand how the concentration of pollutants affects the adsorbent surface at a constant temperature, i.e., it studies the relationship between the amount of adsorbent and the concentration of the pollutant in the solution at adsorption equilibrium. These studies are essential in adsorption experiments because they provide valuable information about the efficiency of the adsorbent, its adsorption capacity, and the way the pollutant interacts with the adsorbent surface. The importance of these studies lies in their ability to provide data on the dynamic behavior of the adsorbent and to determine the best operating conditions for the adsorption process. Through the results of these studies, the ability of the material to remove pollutants from aqueous solutions under specific conditions can be evaluated, which helps in improving industrial processes for treating polluted water or air. There are several isothermal models that are used to understand these relationships (49). The most prominent is the Langmuir model, which assumes that adsorption occurs on identical sites and that each site interacts with one mole of ions or molecules, with the assumption that adsorption only occurs when the adsorbent sites are completely saturated. The Freundlich model is based on the assumption that the adsorbent sites are not equal and that the degree of adsorption depends on the concentration of the pollutant, reflecting unequal interactions between molecules on the surface of the adsorbent. The adsorption enablement model assumes that adsorption follows a nonlinear pattern and depends on unpredictable changes in concentration. In this model, the pollutant interacts with the adsorbent surface in a complex manner that changes based on concentration gradients and other environmental factors. These models assume that the adsorbent contains fixed or variable sites that can participate in the reactions and

that adsorption occurs at a certain equilibrium between the pollutant ions or molecules and the adsorbent (80). Table 3 shows the general and linear formulas for the isothermal models used to represent the adsorption of thallium (III) to sawdust.

The adsorption results of thallium ions on the sawdust surface were analyzed using different isothermal models: Langmuir, Freundlich, and Temkin, as shown in Table 4. The results of the Langmuir model showed that the correlation coefficient $R^2=0.993$ showed excellent agreement with the experimental data. In the Freundlich model, the correlation coefficient $R^2=0.9177$ showed good agreement. For the Temkin model, the results showed a good fit with $R^2=0.9295$, indicating a moderate effect of energy on the adsorption process.

where q_e is the adsorption capacity at equilibrium state ($\text{mg}\cdot\text{g}^{-1}$), C_e is the equilibrium adsorbed concentration ($\text{mg}\cdot\text{g}^{-1}$), q_{max} is the maximum adsorption capacity of the Langmuir model ($\text{mg}\cdot\text{g}^{-1}$), K_L is the constant of Langmuir adsorption isotherm model expressed binding sites ($\text{l}\cdot\text{mg}^{-1}$), R_L is the separation factor in the Langmuir model (dimensionless), K_F is the constant of the Freundlich adsorption isotherm model ($\text{mg}\cdot\text{g}^{-1}\cdot(\text{l}\cdot\text{mg}^{-1})^{1/n}$), n is the intensity of adsorption in the Freundlich model (dimensionless), K_T is the Temkin isotherm equilibrium binding constant ($\text{l}\cdot\text{mg}^{-1}$), R is the universal gas constant ($8.3144 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$), b is the constant in the Temkin isotherm model (dimensionless), and T is absolute temperature (K)

Adsorption kinetics study

In adsorption experiments, kinetic studies are a fundamental method for understanding how contaminants interact with adsorbent surfaces over time. These studies reveal the mechanisms of contaminant removal from solutions, and help determine the factors affecting the speed and efficiency of adsorption, such as adsorbent properties, contaminant concentration, and temperature.

Table 3. Details of isothermal models used in this study

Isotherm model	Form of the model's equation		Slop term	Intercept term	Augmented parameter
	General	Linear			
Langmuir	$q_e = \frac{q_{max} \cdot K_L C_e}{1 + K_L C_e}$	$\frac{1}{q_e} = \frac{1}{q_{max} K_L} \frac{1}{C_e} + \frac{1}{q_{max}}$	$\frac{1}{q_{max} K_L}$	$\frac{1}{q_{max}}$	$R_L = \frac{1}{1 + K_L C_e}$
Freundlich	$q_e = K_F C_e^{1/n}$	$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e$	$\frac{1}{n}$	$\ln K_F$	-
Temkin	$q_e = \frac{RT}{b} \ln K_T + \frac{RT}{b} \ln C_e$	$q_e = \frac{RT}{b} \ln K_T + \frac{RT}{b} \ln C_e$	$\frac{RT}{b}$	$\frac{RT}{b} \ln K_T$	-

Table 4. Constants of isothermal models used in the current study

Langmuir isotherm model				Freundlich isotherm model			Temkin isotherm model		
q_{max}	K_L	R_L	R^2	K_F	n	R^2	K_T	b	R^2
1.6717	0.6667	0.0164	0.993	1.2555	15.3846	0.9177	0.6375	24.9378	0.9295

In fact, kinetic studies help in selecting the best adsorbents and reaction methods that enhance the pollutant removal efficiency in environmental and industrial applications (48). One of the most important kinetic models used in the study of adsorption is the pseudo-first order model. This model is based on the assumption that the adsorption rate is proportional to the concentration of the contaminant remaining in the solution. In other words, the rate of adsorption of the contaminant increases with the increase in the concentration of the contaminant in the solution and then gradually decreases with the decrease in the residual concentration. This model assumes that all sites on the surface of the adsorbent are equally capable of interacting with the contaminant, and there are no complications or changes in the properties of these sites (81). The pseudo-second order model assumes that adsorption depends on the concentration of the contaminant in the solution, but this relationship is more complex. In this model, the rate of adsorption is assumed to be proportional to the square of the residual contaminant concentration, indicating that most adsorption occurs very quickly at first and then slows down over time. This model is more accurate in explaining processes that rely on the adsorption of contaminants that interact intricately with adsorbent surface sites. Another popular model is the Elovich Model, which assumes that adsorption occurs on an adsorbent surface that contains sites of unequal energy, i.e., some sites have a higher capacity to adsorb than others (82). The adsorption rate is assumed to decrease with time, meaning that the adsorbent begins to adsorb rapidly and then the adsorption rate decreases as the high-energy sites become filled. The model reflects the dynamic nature of adsorption, whereby sites with higher reactivity become occupied more quickly. The intra-particle diffusion model is based on the assumption that the kinetic process of adsorption is not only related to the interaction of the contaminant with the adsorbent, but also depends on how the contaminants move within the pores or molecules. This model envisions adsorption as occurring in two stages: the first is the surface transport of the contaminant to the surface of the adsorbent, and the second is the intra-pore transport where the molecules move through the pores available for adsorption. This model reflects the significant influence of the spatial distribution of the pores on the adsorption process (49). Based on these models, the different stages a contaminant goes through during its interaction with the adsorbent can be identified, helping to improve the experimental design and determine the best operating conditions for effective contaminant removal. Table S1 shows the details of the kinetic models used in the present study to describe the adsorption of thallium (III) using sawdust.

Table S2 shows the behavior of kinetic models used to describe thallium adsorption by sawdust, in addition to the values of the constants of these models. When analyzing the results obtained from applying the different kinetic models (pseudo-first-order, pseudo-second-order, Elovich model, and intra-particle diffusion model), it is noted that the pseudo-first-order model gave a relatively

low correlation coefficient (R^2) of 0.6706, which indicates that this model is not the most suitable for describing the kinetics in this experiment. The results obtained in this study showed that the pseudo-second-order model did not provide a good fit with the experimental data, as the correlation coefficient (R^2) was 0.5986, which is the lowest value compared to the other models, indicating that the adsorption results do not match well with the basic assumptions of this model. The Elovich model provided reasonable values with a high correlation coefficient of 0.9846, which reflects the ability of the Elovich model to explain the obtained data in an acceptable way. In the intra-particle diffusion model yielded a velocity constant of (k_p) 0.093 with $I = -0.2124$ and the highest correlation coefficient compared to the other models with $R^2 = 0.9975$.

Discussion

Investigation of BET surface area

The result of surface area before adsorption of thallium (III) indicates that the adsorbent has pores and active sites that contribute to its ability to adsorb pollutants, making it an effective material for adsorption processes. The nature of sawdust, which has hydroxyl and carboxyl functional groups on its surface, enhances its ability to interact with pollutants by forming strong chemical bonds. In addition, the micropores on its surface increase the interaction by providing additional sites for the adsorption process. After the adsorption process, the active pores were filled with thallium ions. As the pores are closed, the available surface area was significantly reduced. The accumulation of thallium ions on the outer surface of the sawdust contributed to the formation of layers covering the pores. Moreover, the significant decrease in surface area indicated that the adsorption was not limited to the outer surface only, but also extended into the interior of the micropores, resulting in the complete saturation of the porous structure. On the other hand, the decrease in surface area may also be due to the deposition of complexes between thallium and functional groups on the surface, which promotes the formation of non-porous layers that reduce the future interaction of active sites. This change clearly indicates that the surface structure of the sawdust underwent a major physical and chemical transformation as a result of adsorption, with the structure becoming denser and less porous, reflecting the consumption of most of the available active sites on the surface during the process (83).

Investigation of FT-IR analysis: Studying the FTIR spectrum before adsorption of thallium ions using sawdust adsorbent, a clear broad peak appears at 3291 cm^{-1} representing the stretching vibrations of the O–H bond in the hydroxyl groups attached to cellulose and hemicellulose. After the adsorption, the peak splits into two peaks at 3230 cm^{-1} and 3165 cm^{-1} , indicating the interference of thallium ions with these hydroxyl bonds and the reduction of vibrational energy as a result of the formation of new bonds with thallium. The 3008 cm^{-1} peak indicates the C–H bonds were also affected, reflecting

possible interactions of the target ion with the methyl or methine groups, while the 2877 cm^{-1} peak indicates the C–H bonds in the methyl groups. In addition, the 1758 cm^{-1} peak before adsorption, which is due to the C=O bond in the carboxylic or ester groups, shows obvious changes after adsorption with new peaks at 1738 cm^{-1} and 1685 cm^{-1} , indicating that thallium was attached to the carboxylic groups in the sawdust structure, affecting the vibration nature of these bonds (84). The peaks at 1541 cm^{-1} and 1697 cm^{-1} , which represent the aromatic rings in lignin, were also affected, giving rise to new peaks at 1531 cm^{-1} and 1486 cm^{-1} after adsorption, indicating the interaction of thallium ions with the aromatic rings and changes in the chemical environment of these sites. In the range of $1387\text{--}1211\text{ cm}^{-1}$ before adsorption, which represents the vibrations associated with C–O and C–O–C bonds in cellulose and hemicellulose, noticeable changes appeared after adsorption with new peaks appearing at 1213 cm^{-1} and 1132 cm^{-1} . These changes confirm that thallium ions had interacted with the ether and hydroxyl bonds, modifying the vibrational energy of these bonds. The peaks at 834 cm^{-1} and 720 cm^{-1} , which represent the out-of-plane vibrations of the aromatic rings, showed additional changes indicating structural interactions between thallium and the aromatic compounds in lignin. Overall, the analysis showed that thallium ions interacted with functional groups, such as hydroxyl and carboxylic groups, in sawdust aromatic rings and ether bonds. These interactions resulted in obvious changes in the FTIR spectrum, highlighting the role of sawdust as an effective medium for thallium adsorption via forming new bonds or modifying the chemical environment of functional groups (34).

Investigation of SEM test

Before thallium adsorption, the surface texture of the sawdust has a rough, multi-dimensional texture, reflecting the natural structure of cellulose, hemicellulose, and lignin. There were no deposits or coatings on the surface, indicating that the surface was free of any foreign matter or previous adsorption. After adsorption, the pores and voids were clearly less visible, with some pores appearing to be partially or completely filled with sediment. These changes indicate that thallium ions had accumulated on the surface and inside the pores, partially or completely covering the active sites. The observed precipitates were due to the precipitation of thallium in the form of complexes with functional groups present on the surface of the sawdust (such as hydroxyl and carboxyl groups). In addition, changes in surface roughness can be observed. After adsorption, the surface appears smoother or less regular, indicating that the chemical interaction between thallium ions and functional groups on the sawdust surface had modified the surface structure. This modification may result from the formation of chemical bonds between thallium and active groups or the accumulation of thallium in multiple layers (85).

Investigation of point of zero charge

The results show a strong adsorption of H^+ ions due to their interaction with surface functional groups, such as carboxyl ($-\text{COOH}$) and hydroxyl ($-\text{OH}$), which become positively charged by protonation. As pH increases towards the pH_{pzc} value (between 3 and 4), the surface reaches a charge equilibrium, where the positive and negative charges are equal, resulting in a ΔpH close to zero. When the value of pH increases, the carboxyl groups are converted to negative carboxylates ($-\text{COO}^-$), and hydroxyl groups are converted to oxide ions ($-\text{O}^-$), causing an increase in the negative charge on the surface and a gradual increase in positive ΔpH values. At very high initial pH, the negative surface charge increases to a maximum due to the abundance of OH^- ions that promote the deprotonation of the surface. These results reflect the ability of sawdust to interact with ions due to its chemical composition rich in diverse functional groups, such as cellulose, hemicellulose, and lignin, as well as its porous structure, which increases the interaction area, making it an effective material for adsorption processes. These results indicate that pH_{pzc} plays a crucial role in determining the adsorption mechanism. At pH higher than pH_{pzc} , the surface becomes negatively charged, which enhances the electrostatic attraction of positively charged thallium ions and increases the adsorption efficiency. At pH lower than pH_{pzc} , the electrostatic repulsion between the positive surface and thallium ions limits the adsorption efficiency. These properties demonstrate that sawdust, with its chemical composition rich in diverse functional groups and large porous structure, is an effective material for removing thallium ions from aqueous solutions, especially when the pH is optimally controlled (63). Therefore, the solution was studied at pH in the range of 3–10.

Investigation of acidity impact

At low pH values, between 3 and 6, the removal ratio (%R) ranges from 9.6% to 35.5%. At this stage, the concentration of H^+ ions is high, which leads to intense competition between these ions and thallium (III) ions for the active adsorption sites. In addition, the results of the point of zero charge (pH_{pzc}) of sawdust, which is about 5.2, show that the surface is positively charged at these low pH values, which causes electrostatic repulsion of positive thallium ions and weakens the adsorption efficiency. As the pH increases, the surface gradually loses protons, becoming negatively charged. This transformation is consistent with the results of pH_{pzc} , where the surface becomes more attractive to positive thallium ions. At this point, the electrostatic interaction between the thallium ions and the sawdust surface is enhanced, leading to increased removal efficiency. At high pH values, the removal ratio increases sharply to 93–100 at pH 7–10, respectively, due to the shift of the dominant mechanism from adsorption to chemical precipitation. At these values, thallium (III) ions react with OH^- ions to form the insoluble thallium hydroxide complex ($\text{Tl}(\text{OH})_3^{-3}$), which leads to complete precipitation of thallium as a white layer at the bottom of

the adsorption flask. This relation between the pH and zero charge point results shows that the large ΔpH values at high pH values are a clear indication of the precipitation of heavy metal hydroxides as the main mechanism for thallium removal, explaining the dramatic shift in removal efficiency in these conditions (13).

Investigation of agitation speed impact

The behavior of the agitation speed can be explained by improved solution mixing, which promotes homogeneous distribution of thallium ions and increases the probability of collision between ions and active adsorption sites on the sawdust surface. With an increase in the agitation speed from 300 to 450 rpm, the mobility of molecules is further improved, reducing the thickness of the boundary layer surrounding the sawdust particles, facilitating mass transfer and increasing the adsorption rate. At an agitation speed of 450 rpm, the stability indicates that the process has reached a dynamic equilibrium state. In this case, the active adsorption sites on the sawdust surface have been fully utilized, and increasing the agitation speed does not lead to further improvement in mass transfer or adsorption. Overall, these results show that agitation speed is a major factor affecting the adsorption efficiency until a critical speed (450 rpm) is reached. After that, a surface saturation state and a balance between fluid dynamics and adsorbent surface properties is reached, limiting the effect of agitation (81).

Investigation of initial concentration impact

The behavior of initial concentration on the recovery efficiency of thallium from contaminated aqueous solutions is due to the presence of a large number of active sites on the surface of the sawdust at the beginning of the experiment, where the surface area of $22.3 \text{ m}^2/\text{g}$ is sufficient to interact with all the thallium ions in the solution. At this stage, there is a balance between the number of available sites and the number of ions, resulting in a high adsorption efficiency. The decrease of the removal efficiency between 30 and 100 ppm can be explained by the gradual saturation of the active sites. At these concentrations, the limited surface area of the sawdust becomes a limiting factor, as it cannot accommodate the increasing numbers of ions available in the solution. Furthermore, competition between thallium ions for the remaining active sites reduces the adsorption efficiency (86). At initial concentrations of 90 ppm and above, the stability indicates that the adsorbent has reached adsorption saturation. At this point, all active sites have been fully utilized, and the adsorbent can no longer hold more ions, regardless of the increase in initial concentration. In addition, the low surface area after adsorption ($1.17 \text{ m}^2/\text{g}$) explains the stability of the amount of adsorbed thallium. This shift shows how the effective surface area gradually decreases as the active sites become filled, leading to reduced adsorption opportunities at higher concentrations. Thus, the results show that the removal efficiency directly depends on the ratio of thallium ions

to the number of active sites and the effective surface area of the sawdust. While the material shows high thallium removal efficiency at low concentrations, surface area limitations lead to saturation of the sites and decreased efficiency at high concentrations (54).

Investigation of adsorbent dosage impact

The gradual increase indicates that increasing the amount of sawdust provides more surface area and more active sites on the surface of the material, which enhances the ability of sawdust to adsorb thallium ions from the solution. After the percentage removal of thallium reaches the highest value, the adsorbent has reached the saturation state, where no additional thallium ions are adsorbed despite increasing the adsorbent dose (at the present conditions), and thus there is no further improvement in the removal ratio after this dose. The interpretation of these results is closely related to the surface area available on the sawdust and the number of active sites. As the amount of sawdust added increases, more sites are provided for the ions to interact with the adsorbent surface, increasing the adsorption capacity. But after a certain point, when all active sites become saturated, adsorption saturation occurs and the adsorption does not increase further. Based on these results, it can be concluded that the optimum dosage of sawdust to achieve the best removal of thallium ions is 6 g, where the efficiency reaches the highest level, and the removal process is carried out with maximum efficiency (85).

Investigation of contact time impact

Initially, at 10 min contact, the %R removal ratio was low (7.22%), indicating that the adsorption process had not started as efficiently as required in this short time period. With increasing contact time, a steady increase in the removal percentage was observed, reaching 53.08% at 60 min and 92.12% at 150 min. This remarkable improvement is due to the increased interaction time between the thallium ions and the sawdust, allowing sufficient time for the ions to reach their active sites on the surface of the adsorbent. Initially, the ions were rapidly adsorbed on the outer surface of the sawdust, but as time went on, deeper adsorption occurred within the micropores of the adsorbent. After 150 min, the sawdust had reached the saturation state. At this point, all available active sites on the sawdust surface had adsorbed ions, and there were no sites to receive any additional thallium, resulting in a stable removal percentage. This behavior indicates that the interaction between the ions and the adsorbent undergoes rapid initial stages of adsorption followed by a gradual stabilization stage until saturation is reached. Based on these results, it can be concluded that the optimum contact time for thallium removal using sawdust is around 150 min, where the highest removal efficiency is achieved (82).

Investigation of temperature impact

At low temperatures such as 25°C , the adsorption process

was more efficient, as the rate of movement of molecules and ions in the solution is relatively slow, allowing the ions to interact better with the surface of the sawdust. In these conditions, the available surface area of the adsorbent probably had a greater opportunity to interact with the ions, enhancing the removal process. A decrease in adsorption efficiency was observed with increasing temperature. This is probably because as the temperature increases, the ions in the solution begin to move more quickly, reducing the chance of interaction with the sawdust surface. This may reduce the ability of the adsorbent to absorb ions, especially if the high temperature changes the properties of the adsorbent surface. Furthermore, the increase in temperature may contribute to the induction of some chemical reactions that may cause the ions to interact less effectively with the sawdust surface, resulting in a lower removal rate. Another possible reason is that higher temperatures may reduce the ability of sawdust to retain ions due to changes in structure, porosity, or even specific surface interactions between thallium and the adsorbent. Based on these results, it can be concluded that sawdust is more effective in removing thallium ions at lower temperatures, as it provides a more favorable environment for the ions to interact with the adsorbent (59).

Investigation the adsorption thermodynamic behavior

The negative value of enthalpy indicates that the process is more effective at lower temperatures, where adsorption releases heat due to a strong interaction between the thallium ions and the sawdust surface. This result is in line with our earlier results on effect of temperature on removal efficiency, where a decrease in the removal efficiency was observed with increasing temperature. In this study, the removal percentage decreased significantly from 92.12% at 25 °C to 4.04% at 50 °C, which illustrates the significant effect of temperature on the reaction. Therefore, it can be concluded that the reaction is not just a simple mechanical reaction, but involves strong interactions at the molecular level between thallium ions and the sawdust substrate, which is consistent with the negative enthalpy. The negative entropy indicates that the transition from the liquid to the surface of the adsorbent reduces randomness, which enhances the stability of the system and contributes to the organization of molecules on the surface of the adsorbent (66). As for the free energy (ΔG), the negative values obtained at different temperatures confirm that the adsorption process is a spontaneous process ($\Delta G < 0$), reflecting the ability of the system to effectively remove thallium ions without the need for external energy intervention. However, the values shown by the study indicate that the process becomes less spontaneous with increasing temperature, which is consistent with data obtained from the temperature effect experiments. These results were also correlated with the Fourier transform infrared (FT-IR) and scanning electron microscopy (SEM) results, which showed that the active surfaces of sawdust become more adsorbable at low temperatures, which

enhances the environmental effects of the adsorption process. Based on these results, it can be concluded that sawdust adsorption is an effective process for removing thallium ions in cold environmental conditions, where low temperature provides an ideal environment for increasing the removal efficiency (60).

Investigation the adsorption isothermal behavior

The test results were in agreement with the Langmuir model, indicating that the adsorption follows a single-site mechanism with the surface approaching saturation at certain thallium concentrations. The constant $K_L = 0.6667$ indicates the moderate ability of sawdust to adsorb thallium, while the separation coefficient $R_L = 0.0164$ indicates an effective adsorption process. The results of the Freundlich model indicated that the adsorption occurred on a heterogeneous surface. However, the value of $n = 15.3846$ was unexpected, as the high value indicates that the adsorption process may involve very strong interactions between the ions and the sawdust surface, which could be explained by the presence of heterogeneous adsorption sites or unusual active energy on the surface of the adsorbent. For the Temkin model, the constant $K_T = 0.6375$ showed moderate interaction between the sawdust surface and thallium ions, while the constant $b = 24.9378$ reflected a balanced effect of energy. When these results are combined with the results of the Fourier transform infrared (FT-IR) analysis, the spectrum shows changes in the functional groups on the sawdust surface after interaction with thallium ions, such as changes in the chemical bonds of the hydroxyl and carboxylic groups. These changes support the hypothesis that the sawdust surface actively participates in the interaction with thallium, which reinforces the results of the different adsorption models. The results of scanning electron microscopy (SEM) analysis also showed obvious changes in the surface morphology after adsorption, including an increase in porosity and a change in the shape of the adsorbent sites, indicating the deep interaction of thallium with the surface of sawdust. Based on these results, it can be concluded that the adsorption of thallium on the surface of sawdust occurs through a complex and heterogeneous mechanism. The agreement of the Langmuir model with the experimental data supports the hypothesis of limited adsorption sites on the surface, while the Freundlich model results indicate strong and deep interactions. The Temkin model results suggest a moderate energy effect on the interaction (58). All these results are supported by FT-IR and SEM data that show the chemical and physical changes that occur on the surface of the adsorbent, highlighting the effectiveness of sawdust as an adsorbent for heavy ions such as thallium.

Investigation the adsorption kinetics behavior

For the pseudo-first-order model, the value of the reaction constant k_1 , indicates a relatively slow rate for the adsorption process, which is consistent with the results indicating that the adsorption did not reach equilibrium

quickly. This model is usually expected to provide a higher correlation coefficient if the adsorption process is dominated by chemical or physical interactions on the surface of the adsorbent material in a way that mainly depends on the interaction between ions and the surface of the material. The result of the Elovich model indicate that the adsorption in this case may be heterogeneous on the surface of the adsorbent and may occur on sites with unequal energies. The value of $\alpha = 0.0308$ indicates the beginning of the adsorption process, while the value of $\beta = 3.6523$ shows the decline in the adsorption capacity with time. With these values, the model describes a heterogeneous reaction with a gradual slowdown in the adsorption process as the high-energy sites are filled. This supports the hypothesis of the occurrence of complex reactions that may include chemical or physical reactions on the surface of the adsorbent. The high correlation coefficient indicates that intra-pore diffusion is the main factor determining the adsorption rate. This means that the process depends on the transport of thallium ions through the pores within the adsorbent, which is a more complex process involving the spatial distribution of contaminants within the particles (61). The negative value of I indicates that the intra-particle diffusion phase may not be the only factor affecting it, but the influence of other factors may be limited. There are several hypotheses to explain this, including that diffusion does not occur only in the pores, i.e. there may be additional factors affecting the adsorption process, such as chemical interactions between the adsorbent and the adsorbed ions, or effects resulting from attraction or electrostatic effects. There is also the possibility that the transition phase may not be linear, meaning that the diffusion transition may be more complex than expected, since the transition inside the pores passes through stages with unsteady dynamics. As the ions interact with the surface of the adsorbent in a way that leads to the accumulation or precipitation of some ions faster or slower than normal expectations, it is also possible that there is precipitation of contaminants. This has been confirmed, as the material began to precipitate at a pH exceeding 6 (80). The adsorption process is not limited to simple diffusion within the pores, but is also affected by other factors such as chemical interactions between the adsorbed ions and the surface of the adsorbent, which hinder or accelerate the transport of ions. This may also reflect the effects of precipitation or other chemical interactions occurring in the solution. Hence, we conclude that the intramolecular diffusion model is the closest to describing the adsorption kinetics of thallium on the surface of sawdust (57).

Conclusion

The results of the present study showed that sawdust has high efficiency in removing thallium ions under different operating conditions. The dose of 6 g sawdust achieved the best removal (approximately 92%) at room temperature for 90 ppm of thallium, at pH=6, agitation speed of 450

rpm, and contact time of 150 min. The removal efficiency was directly proportional to pH, agitation speed, contact time, and adsorption dose and inversely proportional to other variables. The obtained results indicated that the surface area decreased from 22.3 for virgin sawdust to 1.17 m²/g at the end of the adsorption process, and the Fourier transform infrared (FT-IR) test confirmed that the adsorbent material contains many functional groups that can play a role in achieving high efficiency in the adsorption process. The SEM test showed that sawdust went through several noticeable changes as a result of thallium treatment due to its porous structure. The results showed that the Langmuir model was the closest to representing the adsorption isotherm and that the intra-particle diffusion model was the best in describing the adsorption kinetics. The thermodynamic study confirmed that the adsorption is spontaneous, exothermic, and has decreasing entropy at low temperatures.

Acknowledgments

The authors would like to thank Mustansiriyah University (<https://www.uomustansiriyah.edu.iq>), Baghdad, Iraq, for its support in the present work.

Authors' Contribution

Conceptualization: Ali Abed Salman, Mohammed Nsaif Abbas.

Data curation: Yasir A. J. Alhamadani.

Formal analysis: Younus Mohammed Abed, Mohammed Nsaif Abbas.

Funding acquisition: Reem Wael Shahadha, Yasir A. J. Alhamadani.

Investigation: Mohammed Nsaif Abbas, Reem Wael Shahadha, Younus Mohammed Abed.

Methodology: Mohammed Nsaif Abbas, Ali Abed Salman, Yasir A. J. Alhamadani.

Project administration: Ali Abed Salman.

Resources: Ali Abed Salman, Reem Wael Shahadha, Yasir A. J. Alhamadani.

Software: Mohammed Nsaif Abbas, Reem Wael Shahadha.

Supervision: Mohammed Nsaif Abbas.

Validation: Ali Abed Salman and Yasir A. J. Alhamadani.

Visualization: Ali Abed Salman, Mohammed Nsaif Abbas.

Writing—original draft: Yasir A. J. Alhamadani, Reem Wael Shahadha, Younus Mohammed Abed.

Writing—review and editing: Mohammed Nsaif Abbas, Ali Abed Salman.

Competing Interests

The authors declare that they have no conflict of interests.

Ethical Approval

The authors confirm that this study did not involve human participants, animal subjects, or any form of experimentation on living organisms. No surveys, interviews, or personal data were collected. All contributions to the research and manuscript preparation were made solely by the authors. As such, ethical approval was not required for this study.

Funding

The authors affirm that this paper was entirely self-financed and did not receive any external funding from any source.

Supplementary File

Supplementary file contains Figure S1- S5, Table S1, and S2.

References

- Mulyati S, Hasan N, Kamaludin A, Irianto R, Aripin S.

- Combination of pozzolan and sawdust as biofilter for textile wastewater treatment. *Environmental Health Engineering and Management* 2024;11:9–14. doi:10.34172/EHEM.2024.02
2. Hashem NS, Atiya Ali GA, Jameel HT, Khurshid AN, Abbas MN. Heavy metals evaluation by atomic spectroscopy for different parts of water hyacinth (*Eichhornia crassipes*) plants: banks of Tigris river and Al-Zuhairat village sites. *Biochemical & Cellular Archives* 2021;21(2):3813–19.
 3. Khaleel LR, Al-Hermizy SM, Abbas MN. Statistical indicators for evaluating the effect of heavy metals on Samaraa drug industry water exposed to the sun and freezing. *TJNPR*. 2022;6(12):1969–74. doi:10.26538/tjnpr/v6i12.12
 4. Mohammed Abed Y, Abed Salman A, Jawad Alhamd S, Nsaif Abbas M, Al-Obaidi MA, Hasan Challoor S. Effective removal of stannous ions from aqueous solutions using mango peels: adsorption performance and mechanistic visions. *International Journal of Environmental Analytical Chemistry* 2026;106(3):562–84. doi:10.1080/03067319.2025.2519870
 5. Abdulkareem WS, AlJumaily HSM, Mushatat HA. Management of agro-waste by using as an additive to concrete and its role in reducing cost production: impact of compressive strength as a case study. *IJTPE* 2023;15(1):62–7.
 6. YM Abed, F Allawi, SM Ali, SJ Alhamd, TA Ibrahim, MN Abbas. Implementing a sustainability approach by converting plastic bottle waste from a mischievous substance to a beneficial material by means of zero residue level concept. *Karbala International Journal of Modern Science* 2025;11(3):396–411. doi:10.33640/2405-609X.3413
 7. Nsaif M, Saeed S. The predisposition of Iraqi rice husk to remove heavy metals from aqueous solutions and capitalized from waste residue. *Res J Appl Sci Eng Technol* 2013;6(22):4237–46.
 8. Abbas MN, Al-Madhhachi A-ST, Esmael SA. Quantifying soil erodibility parameters due to wastewater chemicals. *International Journal of Hydrology Science and Technology* 2019;9(5):550–68. doi:10.1504/IJHST.2019.102915
 9. Hung DT, Van Hiep C, Khang PD, Hai NX, Anh NN, Dinh DA, et al. Gamma spectrum stabilization for environmental radiation monitoring stations using NaI(TL) detector. *Radiat Prot Dosimetry* 2020;189(1):48–55. doi:10.1093/rpd/ncaa011
 10. Jin X, Baghayeri M, Nodehi M, Koshki MS, Ramezani A, Fayazi M, et al. Evaluation of thallium ion as an effective ion in human health using an electrochemical sensor. *Environ Res* 2023;238(Pt 1):117026. doi:10.1016/j.envres.2023.117026
 11. Environment and Climate Change Canada, Health Canada: "Assessment-Thallium and its compounds" March, 2024 — confirms use in fireworks, electrical components, and optical applications. Available from: <https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/assessment-thallium-compounds.html>
 12. Fujihara J, Nishimoto N. Thallium - poisoner's poison: An overview and review of current knowledge on the toxicological effects and mechanisms. *Curr Res Toxicol* 2024;6:100157. doi:10.1016/j.crttox.2024.100157
 13. Jadooa ZA, Alsarayreh AA, Abbas MN. Adsorption of thallium using tangerine peels and exploitation from the waste in an eco-friendly manner. *Ecological Engineering & Environmental Technology* 2025;26(2):131–52. doi:10.12912/27197050/196880
 14. McDermott FM, Kan AA, Hunault CC, Robben JH, de Lange DW, Dijkman MA. Case report: Successful treatment of a thallium sulfate intoxication in a dog with use of Prussian blue. *Front Vet Sci* 2025;12:1528327. doi:10.3389/fvets.2025.1528327
 15. Correia MS, Lopez AM. Case Files of the Medical Toxicology Fellowship at the Oregon Poison Center: Thallotoxicosis. *J Med Toxicol* 2022;18(3):248–55. doi:10.1007/s13181-022-00880-9
 16. Wang TT, Wen B, Yu XN, Ji ZG, Sun YY, Li Y, et al. Early diagnosis, treatment, and outcomes of five patients with acute thallium poisoning. *World J Clin Cases* 2021;9(19):5082–91. doi:10.12998/wjcc.v9.i19.5082
 17. Al Hammouri F, Darwazeh G, Said A, Ghosh RA. Acute thallium poisoning: series of ten cases. *J Med Toxicol* 2011;7(4):306–11. doi:10.1007/s13181-011-0165-3
 18. Jimenez O, Cáceres H, Gimenez L, Soto L, Montenegro M, Rueda JAA. Thallium poisoning: a case report. *J Yeungnam Med Sci* 2023;40(3):311–4. doi:10.12701/jyms.2022.00647
 19. Genchi G, Carocci A, Lauria G, Sinicropi MS, Catalano A. Thallium Use, Toxicity, and Detoxification Therapy: An Overview. *Applied Sciences* 2021;11(18):8322.
 20. Gupta RC. Chapter 57 - Non-anticoagulant rodenticides. In: Gupta RC, editor. *Veterinary Toxicology (Second Edition)*. Boston: Academic Press; 2012. p. 698–711. doi:10.1016/B978-0-12-385926-6.00068-5
 21. Yumoto T, Tsukahara K, Naito H, Iida A, Nakao A. A Successfully Treated Case of Criminal Thallium Poisoning. *J Clin Diagn Res* 2017;11(4):Od01–od2. doi:10.7860/jcdr/2017/24286.9494
 22. Sánchez-Chapul L, Santamaría A, Aschner M, Ke T, Tinkov AA, Túnez I, et al. Thallium-induced DNA damage, genetic, and epigenetic alterations. *Front Genet* 2023;14:1168713. doi:10.3389/fgene.2023.1168713
 23. Peter AL, Viraraghavan T. Thallium: a review of public health and environmental concerns. *Environ Int* 2005;31(4):493–501. doi:10.1016/j.envint.2004.09.003
 24. Karbowska B. Presence of thallium in the environment: sources of contaminations, distribution and monitoring methods. *Environmental Monitoring and Assessment* 2016;188(11):640. doi:10.1007/s10661-016-5647-y
 25. Agency for Toxic Substances and Disease Registry (ATSDR) Toxicological Profiles. Toxicological Profile for Thallium. Atlanta (GA): Agency for Toxic Substances and Disease Registry (US); 1992.
 26. Álvarez-Barrera L, Mateos-Nava RA, Hernández-Córdova KN, Lezama-Sánchez E, Alcántara-Mejía VA, Rodríguez-Mercado JJ. Transplacental and genotoxicity effects of thallium(I) during organogenesis in mice. *Toxicol Rep* 2025;14:101896. doi:10.1016/j.toxrep.2025.101896
 27. Weinstein DF, Co JPT. Predictions and Prescriptions for Institutions Sponsoring Graduate Medical Education. *J Grad Med Educ* 2017;9(6):680–2. doi:10.4300/jgme-d-17-00729.1
 28. Markich SJ, Hall JP, Dorsman JM, Brown PL. Thallium toxicity to temperate and tropical marine organisms: Derivation of water quality guidelines to protect marine life. *Mar Pollut Bull* 2023;192:114964. doi:10.1016/j.marpolbul.2023.114964
 29. Alalwan HA, Abbas MN, Abudi ZN, Alminshid AH. Adsorption of thallium ion (Tl⁺³) from aqueous solutions by rice husk in a fixed-bed column: Experiment and prediction of breakthrough curves. *Environmental Technology & Innovation* 2018;12:1–13. doi:10.1016/j.eti.2018.07.001
 30. Rajaa N, Kadhim FJ, Abbas MN, Banyhussan QS. The improvement of concrete strength through the addition of sustainable materials (agro-waste loaded with copper ions). *IOP Conference Series: Earth and Environmental Science* 2023;1232(1):012038. doi:10.1088/1755-1315/1232/1/012038
 31. Abbas M, Turkey S, Abass R. Rice Husks as a Biosorbent Agent for Pb⁺² Ions from Contaminated Aqueous Solutions: A Review. *Biochemical and Cellular Archives* 2020;20:1813–20. doi:10.35124/bca.2020.20.1.1813
 32. Al-Hermizy SMM, Al-Ali SIS, Abdulwahab IA, Abbas MN. Elimination of Zinc Ions (Zn⁺²) from Synthetic Wastewater Using Lemon Peels. *Asian Journal of Water, Environment and Pollution* 2022;19(5):23–9. doi:10.3233/AJW220067
 33. Abbas MN, Abbas FS. Iraqi rice husk potency to eliminate toxic metals from aqueous solutions and utilization from process residues. *Adv Environ Biol* 2013;7(2):308–19.
 34. Alhamd SJ, Manteghian M, Ibrahim TA, Jarmondi KDS.

- Treatment of oil refinery wastewater polluted by heavy metal ions via adsorption technique using non-valuable media: cadmium ions and buckthorn leaves as a study case. *Karbala International Journal of Modern Science*. 2024;10(1):1–18. doi:10.33640/2405-609X.3334
35. Hasan MB, Ibrahim SA, Rahmah NM, Ibrahim TA, Alminshid AH, Abbas MN. Vanadium remediation from polluted wastewater using a novel non-conventional adsorbent. *Results in Engineering* 2025;27:105665. doi:10.1016/j.rineng.2025.105665
 36. Alwan EK, Hammoudi AM, Abd IK, Abd Abd Alaa MO. Synthesis of cobalt iron oxide doped by chromium using sol-gel method and application to remove malachite green dye. *Neuroquantology* 2021;19(8):32–41. doi:10.14704/nq.2021.19.8.nq21110
 37. Alalwan HA, Mohammed MM, Sultan AJ, Abbas MN, Ibrahim TA, Aljaafari HAS, et al. Adsorption of methyl green stain from aqueous solutions using non-conventional adsorbent media: Isothermal kinetic and thermodynamic studies. *Bioresource Technology Reports* 2021;14:100680. doi:10.1016/j.biteb.2021.100680
 38. Abbas MN, Abbas FS. Application of rice husk to remove humic acid from aqueous solutions and profiting from waste leftover. *WSEAS Trans Biol Biomed* 2014;11:62–9.
 39. Alalwan HA, Abbas MN, Alminshid AH. Uptake of cyanide compounds from aqueous solutions by lemon peel with utilising the residue adsorbent as rodenticide. *Indian Chemical Engineer* 2020;62(1):40–51. doi:10.1080/00194506.2019.1623091
 40. Teratogenic Effect of Carbamazepine Drug on the Histological Structure of Testes in the Albino Mouse (*Mus musculus*). *Indian Journal of Forensic Medicine & Toxicology* 2020;14(4):1829–34. doi:10.37506/ijfimt.v14i4.11809
 41. Abd Ali I, Ibrahim TA, Farhan AD, Abbas M. Study of the effect of pesticide 2,4-D on the histological structure of the lungs in the albino mice (*Mus musculus*). *Journal of Pharmaceutical Sciences and Research* 2018;10:1418–21.
 42. Ibrahim TA, Mahdi HS, Abbas RS. Study the effect of Ribavirin drug on the histological structure of the testes in Albino mice (*Mus musculus*). *JGPT* 2020;12(02 Suppl):142-6.
 43. Abbas M, Alalwan H. Catalytic Oxidative and Adsorptive Desulfurization of Heavy Naphtha Fraction. *Korean Chemical Engineering Research* 2019;57:283–8. doi:10.9713/kcer.2019.57.2.283
 44. Ibrahim SA, Hasan MB, Al-Tameemi IM, Ibrahim TA, Abbas MN. Optimization of adsorption unit parameter of hardness remediation from wastewater using low-cost media. *Innovative Infrastructure Solutions* 2021;6(4):200. doi:10.1007/s41062-021-00564-3
 45. Abbas MN. Phosphorus removal from wastewater using rice husk and subsequent utilization of the waste residue. *Desal Water Treat* 2015;55(4):970–7. doi:10.1080/19443994.2014.922494
 46. Ali GAA, Ibrahim SA, Abbas MN. Catalytic adsorptive of nickel metal from Iraqi crude oil using non-conventional catalysts. *Innovative Infrastructure Solutions* 2020;6(1):7. doi:10.1007/s41062-020-00368-x
 47. Abbas MN, Ibrahim SA. Catalytic and thermal desulfurization of light naphtha fraction. *Journal of King Saud University - Engineering Sciences* 2020;32(4):229–35. doi:10.1016/j.jksues.2019.08.001
 48. Yass Khudair S, Alanood AA, Abbas MN. Adsorption of Vanadium from Iraqi Crude Oil on Nano Zeolite and Alum Sludge. *Journal of Engineering and Sustainable Development* 2024;28(6):762–9. doi:10.31272/jeasd.28.6.9
 49. Shadhan Z, Alhamd S, Abbas M. Recovery of vanadium element from wastewater of petroleum refineries using effective adsorbent: Mathematical approach via isothermal, kinetics and thermodynamic simulation. *Al-Qadisiyah Journal for Engineering Sciences* 2024;17:211–9. doi:10.30772/cjes.2024.145441.1069
 50. Maddodi SA, Alalwan HA, Alminshid AH, Abbas MN. Isotherm and computational fluid dynamics analysis of nickel ion adsorption from aqueous solution using activated carbon. *South African Journal of Chemical Engineering* 2020;32:5–12. doi:10.1016/j.sajce.2020.01.002
 51. Abbas M, Abbas FS. The Feasibility of Rice Husk to Remove Minerals From Water by Adsorption and Avail From Wastes. *WSEAS Trans Environ Dev* 2013;9(4):301-13.
 52. Abbas M, Husham Nussrat H. A Statistical Analysis of Experimental Data for the Adsorption Process of Cadmium by Watermelon Rinds in a Continuous Packed Bed Column. *International Journal of Innovation Creativity and Change* 2020;13(3):124-38.
 53. Hasan MB, Al-Tameemi IM, Abbas MN. Orange peels as a sustainable material for treating water polluted with antimony. *J Eco Eng*. 2021;22(2):25-35. doi:10.12911/22998993/130632
 54. Abdullah WR, Alhamadani YAJ, Abass IK. Study of chemical and physical parameters affected on purification of water from inorganic contaminants. *Periodicals of Engineering and Natural Sciences* 2023;11(2):166–75. doi:10.21533/pen.v11.i2.109
 55. Alhamd SJ, Al-Fatlawy HJJ, Ibrahim TA, Abbas ZN. Removal of phenol from oilfield produced water using non-conventional adsorbent medium by an eco-friendly approach. *Karbala International Journal of Modern Science* 2024;10(2):191–210. doi:10.33640/2405-609X.3350
 56. Khaleefa Ali S, Almhana NM, Hussein A, Abbas M. Purification of Aqueous Solutions from Toxic Metals using Laboratory Batch Mode Adsorption Unit: Antimony (V) Ions as a Case Study. *Journal of Green Engineering* 2020;10:10662–80.
 57. Hamed AS, Alsarayreh AA, Abbas MN. Applying of zero residue level concept in integrated management of toxic and solid wastes as a sustainable approach. *Ecol Eng Environ Technol* 2025;26(1):353-378. doi:10.12912/27197050/196409
 58. Alsarayreh AA, Ibrahim SA, Alhamd SJ, Ibrahim TA. Removal of selenium ions from contaminated aqueous solutions by adsorption using lemon peels as a non-conventional medium. *Karbala International Journal of Modern Science* 2024;10(4):511-31. doi:10.33640/2405-609X.3375
 59. Ghulam NA, Abbas MN, Sachit DE. Preparation of synthetic alumina from aluminium foil waste and investigation of its performance in the removal of RG-19 dye from its aqueous solution. *Indian Chemical Engineer* 2020;62(3):301–13. doi:10.1080/00194506.2019.1677512
 60. Ali ST, Shahadha RW, Abdulkareem WS, Abbas MN. Available Low Cost Agro-Waste as an Efficient Medium to Eliminate Heavy Metal Contamination using Sustainable Approach Achieving Zero Residue Level. *Journal of Ecological Engineering* 2024;25(10):160–75. doi:10.12911/22998993/191945
 61. Abbas MN, Mohammed Al-Hermizy SM, Abudi ZN, Ibrahim TA. Phenol Biosorption from Polluted Aqueous Solutions by *Ulva Lactuca* Alga Using Batch Mode Unit. *Journal of Ecological Engineering* 2019;20(6):225–35. doi:10.12911/22998993/109460
 62. Ali GAA, Abbas MN. Atomic spectroscopy technique employed to detect the heavy metals from Iraqi waterbodies using natural bio-filter (*Eichhornia crassipes*) Thera Dejla as a case study. *Syst Rev Pharm* 2020;11(9):264-271. doi:10.31838/srp.2020.9.43
 63. Hameed WA, Abbas MN. Dyes adsorption from contaminated aqueous solution using SiO₂ nanoparticles prepared from extracted tree leaves. *J Eco Eng* 2024;25(7):41–57. doi:10.25130/tjes.31.2.1
 64. Al-Ali SIS, Abudi ZN. Modelling and simulation for the use of natural waste to purified contaminated heavy metals. *Journal of the Nigerian Society of Physical Sciences* 2022;5(1):1143. doi:10.46481/jnps.2023.1143

65. Merabet S, Idder T, Idder A, Gherbi A. Evaluating the accumulation rates of residual sludge and the possibility of their agricultural valorization in a Saharan context: The aerated lagoon wastewater treatment plant at the Ouargla Oasis (Algerian south-east). *Environ Health Eng Manag* 2025;12:1348. doi:10.34172/EHEM.1348
66. Abd Ali IK, Salman SD, Ibrahim TA, Abbas MN. Study of the teratogenic effects of antimony on liver in the adult rabbit (*Oryctolagus cuniculus*). *Advancements in Life Sciences* 2024;11(2):462-9. doi:10.62940/als.v11i2.2773
67. Abbas MN, Ibrahim SA, Abbas ZN, Ibrahim TA. Eggshells as a sustainable source for acetone production. *Journal of King Saud University - Engineering Sciences* 2022;34(6):381-7. doi:10.1016/j.jksues.2021.01.005
68. Hamdi MH, Abbas M, Khaleefa Ali S. Bioethanol production from agricultural waste: a review. *Journal of Engineering and Sustainable Development* 2024;28:233-52. doi:10.31272/jeasd.28.2.7
69. Abbas MN, Al-Tameemi IM, Hasan MB, Al-Madhhachi A-ST. Chemical removal of cobalt and lithium in contaminated soils using promoted white eggshells with different catalysts. *South African Journal of Chemical Engineering* 2021;35:23-32. doi:10.1016/j.sajce.2020.11.002
70. Abbas FS, Abdulkareem WS, Abbas MN. Strength development of plain concrete slabs by the sustainability potential of lead-loaded rice husk (LLRH). *J Appl Eng Sci* 2022;20(1):160-7. doi:10.5937/jaes0-32253
71. Al-Latif F, Ibrahim T, Abbas M. Revealing Potential Histological Changes of Deltamethrin Exposure on Testicular Tissue in Albino Rabbits (*Oryctolagus cuniculus*). *Advancements in Life Sciences* 2024;10:619. doi:10.62940/als.v10i4.2323
72. Alminshid AH, Abbas MN, Alalwan HA, Sultan AJ, Kadhom MA. Aldol condensation reaction of acetone on MgO nanoparticles surface: An in-situ drift investigation. *Molecular Catalysis* 2021;501:111333. doi:10.1016/j.mcat.2020.111333
73. Liu W, Zhang P, Borthwick AG, Chen H, Ni J. Adsorption mechanisms of thallium(I) and thallium(III) by titanate nanotubes: ion-exchange and co-precipitation. *J Colloid Interface Sci* 2014;423:67-75. doi:10.1016/j.jcis.2014.02.030
74. Zhang G, Luo J, Cao H, Hu S, Li H, Wu Z, et al. Highly efficient removal of thallium(I) by facilely fabricated amorphous titanium dioxide from water and wastewater. *Sci Rep* 2022;12(1):72. doi:10.1038/s41598-021-03985-3
75. Kam OR, Bakouan C, Zongo I, Guel B. Removal of Thallium from Aqueous Solutions by Adsorption onto Alumina Nanoparticles. *Processes* 2022;10(9):1826. doi:10.3390/pr10091826
76. Voegelin A, Wick S, Pfenninger N, Mangold S, Baeyens B, Fernandes MM. Thallium adsorption onto phyllosilicate minerals. *Environ Sci Process Impacts* 2022;24(9):1343-59. doi:10.1039/d2em00028h
77. Wick S, Baeyens B, Marques Fernandes M, Voegelin A. Thallium Adsorption onto Illite. *Environ Sci Technol* 2018;52(2):571-80. doi:10.1021/acs.est.7b04485
78. Ali ST, Qadir HT, Moufak SK, Al-Badri MAM, Abbas MN. A statistical study to determine the factors of vitamin D deficiency in men: The city of Baghdad as a model. *Indian J Med Forensic Med Toxicol.* 2020;14(1):691-696.
79. Alsarayreh A. Nickel Remediation by Adsorption Technique Achieving the Concept of Zero Residue Level. *Jordan Journal of Civil Engineering* 2025;19. doi:10.14525/JJCE.v19i1.02
80. Ali SAK, Al-Kaabi Z, Kasim MN, Abbas MN, Ibrahim TA. Remediation of Antimony from Aqueous Solutions by Adsorption Technique: Isothermal, Kinetic and Thermodynamic Studies. *Int J Environ Prot* 2023;43(14):1316-25.
81. Alsarayreh AA, Al-zoubi HQ, Abbas MN. Sustainable nickel removal from water by using waste tea leaves for eco-friendly water treatment. *Indian Chemical Engineer* 2025:1-22. doi:10.1080/00194506.2025.2459833
82. Ibrahim S, Alhamd S, Mudhafar S, Abbas M, Ibrahim T, Alsarayreh A. Remediation of aqueous solutions contaminated by benzidine toxic dye using non-conventional adsorbent: morphological and modelling studies. *Al-Qadisiyah Journal for Engineering Sciences* 2025;18:170-82. doi:10.30772/qjes.2024.149956.1244
83. Ali SAK, Abudi ZN, Abbas MN, Alsaffar MA, Ibrahim TA. Synthesis of Nano-silica Particles using Eucalyptus globulus Leaf Extract and Their Innovative Application as an Adsorbent for Malachite Green Dye. *Russian Journal of Applied Chemistry* 2024;97(1):75-87. doi:10.1134/S1070427224010099
84. Alminshid AH, Alalwan HA, Mohammed MM, Abbas MN. Spectroscopic study of methane reaction mechanism on MgO nanoparticles. *Ionics* 2025;31(4):3861-6. doi:10.1007/s11581-025-06170-y
85. Al-Hermizy SMM, Awadh HA, Abbas MN. Biosorption technique using water hyacinth plant as an effective and sustainable approach for treating oil refinery waste: Vanadium element as a case study. *Journal of Ecological Engineering* 2025;26(6):251-72. doi:10.12911/22998993/202658
86. Ibrahim SA, Alsarayreh AA, Khaled TT, Abbas MN. Buckthorn Leaves as an Efficient Material for Simultaneously Multi Eco-Friendly Purposes. *Journal of Engineering and Sustainable Development* 2025;29(4):539-49. doi:10.31272/jeasd.3033