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RESEARCH ARTICLE

BIOREMEDIATION OF WASTEWATER CONTAMINATED WITH TIN(II) CATIONS USING NON-EXPENSIVE ADSORPTION MEDIUM

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ABSTRACT

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The application of the zero residues level in the removal of tin (II) cations from wastewater using tangerine peels via adsorption technique was the main objective of the current study. A batch-type adsorption unit was used to detect the optimal operating conditions that conducted the maximum percentage removal of target cations. The effect of six major design parameters on the recovery efficiency of tin (II) cations from contaminated aqueous solutions was investigated. Experimental results showed that more than 90% was the maximum tin (II) cation removal efficiency achieved at 150 minutes, 4.5 ppm, 400 rpm, 50°C, and 5.5 and 6 g for contact time, initial concentration of tin (II) cations, agitation speed, temperature, pH, and tangerine peels dosage, respectively. The study also indicated that the treatment efficiency is directly proportional to the agitation speed, the adsorbent dosage, the temperature and the contact time, while the proportional with the initial concentration of tin (II) cations was inversely. The effect of acidity was consistent, being directly proportional within the acidic ranges, and inversely proportional within the basic range.

KEYWORDS

Adsorption, Batch unit, Tin (II) cations, Tangerine peels, and ZRL

1. INTRODUCTION

Tin (Sn) is one of the chemical elements that has played a pivotal role in human life for thousands of years. Its name is closely linked to the development of ancient civilizations, particularly with the discovery of bronze, which was formed from an alloy of copper and tin. This discovery represented a turning point in the course of human development, as bronze was used in the manufacture of tools, weapons, and utensils. Although tin is not a common element in the Earth's crust, with an abundance of only about 2 ppm, its industrial and economic importance has made it an indispensable element in many fields (Khaleel et al., 2022). Tin has a remarkably diverse range of applications. It is used in the manufacture of metal alloys, especially bronze and solder, and in coating steel to protect it from corrosion. This is known as tin plating, which is used in the manufacture of metal cans for preserving food and beverages. In addition, organotin compounds are used in various fields such as the manufacture of pesticides, plastic thermal stabilizers, and the glass and ceramics industries (ATSDR, 2005). Alongside technological progressions, the requirement for tin has escalated in the electronics sector, where it is utilized in the fabrication of electrical conductors and microprocessors. Regardless of its prevalent application, tin possesses detrimental impacts upon confrontation with elevated concentrations, notably its carbon-based derivatives (Khaleel et al., 2022). Long-term contact with tin substances may result in disorders affecting the neural system, hepatic tissue, renal organs, and immune system. Research investigations have demonstrated that tin-organic substances like tributyltin (TBT) represent ecological and clinically hazards, leading to endocrine malformations and

abnormalities in aquatic organisms. Within humans, ingesting elevated levels of tin via meals, water, or other drinks may cause signs like queasiness, throwing up, migraines, and abdominal discomfort (Khaleel et al., 2022). The poisonous levels of tin differ according to its chemical state and the method of its entry into the organism. Non-organic tin is not as harmful as carbon-based compounds; the World Health Organization (WHO) affirms that the acceptable threshold for inorganic tin in potable water must not surpass 2 mg/L (ATSDR, 2005). Regarding natural carbon-based substances like tert-butyltin, these are far more harmful despite minimal levels which might not surpass parts of micrograms per liter. The threat of these substances resides in their capacity to bioconcentrate inside living tissues and their resistance for decomposing in the ecosystem, resulting in extended permanent collective consequences. Amidst escalating contamination stemming from manufacturing and anthropogenic activities, it has grown necessary to advance capable methodologies for eliminating tin and other stannum substances alongside out of soil, water, and air (Abed et al., 2026). One of the most outstanding ways utilized to remediate the pollution of tin and other heavy metals are chemical precipitation, ion exchange, membrane technologies, and biological treatment. Nevertheless, whereas many of the previously mentioned techniques possess benefits, they likewise possess drawbacks that render their ongoing application challenging, for instance, elevated expenses, the requirement for frequent replacement, and the build-up of hazardous residues. In contrast, adsorption is considered one of the most effective and economical methods, relying on the use of solid materials with a high surface area capable of attracting and trapping tin ions. Adsorption is considered one of the most important modern methods for

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removing heavy metals from water, due to its simplicity, low cost, and high effectiveness. Although commonly used adsorbents such as activated carbon, zeolite, alumina, and nanomaterials have proven effective in treating various types of polluted water, high efficiency, but it is required to uninterrupted regeneration have prompted many environmental specialists to search for suitable and inexpensive alternatives (Khudair et al., 2024). From last three decade, agricultural and industrial waste has attracted the attention of researchers because it is a low-cost, readily available material that requires no preparation costs, and its safe and beneficial disposal is a promising environmental goal. In recent decades, scientific research has focused on using agricultural waste as an alternative to activated carbon and other expensive synthetic materials as adsorbents. This waste includes fruit peels such as pomegranate, banana, pineapple, almond, pistachio, tangerine and lemon peels, as well as eggshells (Ali et al., 2020a; Abdullah et al., 202; Ibrahim et al., 2025a; Hamed et al., 2025; Ali et al., 2025; Jadooa et al., 2025; Al-Hermizy et al., 2022). It also includes other agricultural residues such as, sunflower husks, used tea leaves, sawdust, and certain types of algae like water hyacinth, and *Ulva lactuca*, as well as tree leaves such as buckthorn, mandarin, and eucalyptus (Abdulkareem et al., 2023; Al-Ali et al., 2023; Alhamadani et al., 2026; Hashem et al., 2021; Ibrahim et al., 2025b; Mahmood et al., 2025; Alhamadani et al., 2025). In addition to some industrial wastes that have been successfully converted into effective adsorption media, such as, plastic waste, and alum sludge, these wastes have proven efficient in treating various types of pollutants, including water hardness, and petroleum pollutants (Abed et al., 2025; Khudair et al., 2024; Ibrahim et al., 2021). This is true not only for aqueous solutions but also for wastewater, soil, air, and petroleum fraction. These materials are characterized by their adsorption capacity due to the existence of multi-types of active functional groups like hydroxyl (-OH), carboxyl (-COOH), and phenol (-C₆H₅OH), as well as their fibrous structure and relatively large surface area. Although these materials become an

environmental burden after the adsorption process is complete, as they are laden with high concentrations of adsorbed pollutants, which are often toxic, the concept of zero residue has provided a suitable solution to this problem (Hashim et al., 2026). These residues can be used as raw materials in the preparation of useful substances such as acetone, promoted bioethanol and soil fertilizers, or in the preparation of nanomaterials, or concrete additives, especially residues laden with high-density heavy metals such as lead, and copper (Hamdi et al., 2024; Hameed and Abbas, 2024; Rajaa et al., 2023). Among the agricultural wastes that have garnered significant attention in environmental remediation are tangerine peels. These peels contain considerable amounts of organic-base ingredients like lignin, pectin, and cellulose, which include functional groups eligible of capturing the different ions of heavy metal such as tin cations. The huge magnitude of this waste (peels) obtainable in form of residue of the must and food industries make them an important option for applying Zero Residue Level (ZRL) concept. Employing tangerine peels to remediate the aqueous solutions contaminated by tin cations not only presents environmental advantages by handling contamination, but likewise participates to the sustainable management of agro-waste. This investigate aims to study the suitability of tangerine peels (a type of agricultural waste) as a medium for the adsorption of tin(II) cations from contaminated aqueous solutions under various operating conditions in a batch-type adsorption unit.

2. EXPERIMENTAL WORK

2.1 Chemicals

The study required a number of chemical substances to achieve its goal, and these substances were carefully selected, taking into account high-quality origins. Table 1 show the chemicals used to conduct the main aim of the current study.

Table 1: Chemicals used in this study

Substance	Chemical Formula	Molecular Weight (g/mol)	Purity, (%)	Form	Company and Origin
Tin (II) chloride dihydrate	SnCl ₂ ·2H ₂ O	225.65	> 98	White crystal powder	Kesari Scientific Chemicals company, India
Hydrochloric acid	HCl	36.46	37	Clear, colorless liquid	Thomas Baker (Chemicals) Pvt. Ltd., India
Sodium hydroxide	NaOH	40	99.99	White pellets completely soluble in water	HiMedia Laboratories, India
Double-distilled water	H ₂ O	18	> 99.9, 2.5 μS/cm	Colorless liquid	Laboratory Distilled unit

2.2 Devices and Equipment

Several pieces of devices and equipment were used to achieve the study's

objective carefully and accurately. Table 2 explains the information of devices and equipment utilized in the present research.

Table 2: Devices and equipment used in this study

Name of devices or equipment	Model	Company	Origin
Sensitive Electric Analytical Weight Balance	NBK-FA110	NANBEI	China
Drying oven	TR 450	Nabertherm	Germany
Laboratory grinder	RT-04	Mill Powder Tech Co., Ltd.	Taiwan
12-mesh stainless-steel standard round laboratory sieve	HJ-G444	Hebei Huanji Metal Wire Mesh Co., Ltd.	China
Water Bath Orbital Shaker	SHKE7000-1CE	Thermo Scientific	USA
Vacuum Filtration Kit	EIS-CH200501- CP	LabSafety	USA
Filter paper	Whatman No. 41 Quantitative ashless	Cytiva	UK
Borosilicate glass wear	Miscellaneous	Witeg Labortechnik GmbH	Germany
100ml amber round glass jars of double lids	B093341B2B	Chengdu Miroo Bio-Technology Co., Ltd.	China
Atomic absorption spectrophotometer (AAS)	AA 7000	Shimadzu	Japan

2.3 Stock Solution of tin (II) cations

To avoid interference with other metals and substances—both the familiar and the unfamiliar —found in real wastewater, and to determine the

ability of adsorbent material to absorb tin (II) cations, adsorption experiments were conducted using laboratory pre-prepared solutions. These solutions were prepared by diluting specific volumes of a reference

solution, called the stock solution. The stock solution was prepared using tin (II) chloride dihydrate, which was the primary source of tin ions in this study. Accurately 1950 mg of tin (II) chloride dihydrate salt was measured by sensitive balance, before transferred to a clean beaker including solution of 0.24 N hydrochloric acid (HCl) in adequate volume for dissolution. The dissolving salt process was accomplished using a glass rod, and after dissolving, the solution was charged to a clean and sterilize 1000 mL volumetric bottle via a glass funnel to. The volume was then brought up to the mark using acidified water to produce of 1000 mg/L of tin (II) cations stock solution.

2.4 Calibration curve of tin (II) cations

The calibration curve is an essential tool in chemical analysis. It is used to determine the unknown concentration of a sample by comparing its response (such as absorbance in an atomic absorption spectrometer) with the response of a series of solutions of known concentrations prepared using the same method. The prominence of this curve lies in its capability to convert the electronic signal emitted by the instrument into a quantifiable concentration value, thus allowing for the determination of the concentration of the target element in aqueous solutions (Ali et al., 2020b). To prepare an accurate and reliable calibration curve, a series of solutions of the tin (II) cations must first be prepared, based on the stock solution, at different concentrations. The response of each concentration is then measured using a AAS device at 235.5 nm wavelength, and the value of each reading is repeated three times to calculate the mean and reduce the experimental error. The relationship between the response values (on the y-axis) and the known concentrations (on the x-axis) is then plotted. The best straight line passing through the points is drawn, and a linear equation of the form $y = ax + b$ is derived from this line, where a is the slope and b is the intercept. Additionally, the correlation coefficient (R^2) is calculated, which should be close to (1) to indicate good linearity and strong relation between the variables. Finally, this equation is used to calculate the concentration of tin (II) cations in the unknown sample after measuring its response and substituting it into the equation. Figure 1 show the calibration curve of tin (II) cations utilized in the current research.

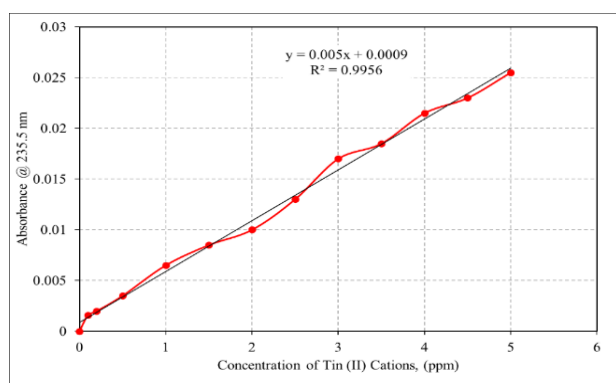


Figure 1: The calibration curve of tin (II) cations utilized in the current research.



Figure 2: Tangerine peels used in the present investigation.

Tangerine Peels (adsorbent): in the current study, the tangerine peels used were collected from Iraqi tangerines produced in the Al-Muqadiyah district, Diyala Governorate during February 2025, and prepared

according to the method described in. Fresh peels were collected from the fruit according to household consumption. The collected peels were taxonomy classified as peels of the Iraqi tangerine plant in the herbarium of the Department of Biology / College of Education for Pure Sciences – University of Diyala. The classified peels, shown in Figure 2, were washed using excess of tap water until they were thoroughly cleaned of all dirt and debris. Afterward, the washed peels were dried by exposing them to open air in a clean, dry place at a temperature of 30-32°C for four days. The drying process was completed by exposing the peels to a temperature of 45 °C in a drying oven to prevent charring. The drying was gone on until the mass of the peels stabilized for no more than 3 hours. The dried peels were ground in a laboratory grinder to obtain a fine powder. The powder was then sieved using a laboratory sieve. The sieved powder was used for the study. The powder was stored in 100 ml amber jars at 4°C until use, to prevent any potential changes in its properties due to humidity or light.

Batch Adsorption Unit: A batch-type adsorption unit was employed to perform tin (II) cation adsorption experiments utilizing tangerine peels as a non-valuable adsorption material. The batch adsorption unit is considered one of the essential pieces of equipment for studying adsorption processes and evaluating their efficiency under specific experimental conditions. This unit consists of a shaking water bath, which is the main component of the process, used to provide a constant temperature and stable vibration. At a specific pH, experimental flasks containing the solution contaminated with tin (II) cations at a specific concentration, along with a dose of tangerine peels, are placed inside the water bath shaker. These flasks are then encased in a layer of aluminum foil tightly secured with rubber bands to prevent any potential effects from light or other unforeseen factors. The operational factors studied to determine the efficiency of adsorption process were temperature, contact time, tangerine peels dosage, pH, agitation speed, and initial concentration of tin(II) cation. The ranges for these factors were 25-50°C, 10-180 minutes, 0.5-6.5 g, 1-8 g, 100-500 rpm, and 0.5-5 ppm tin ions, respectively. After adjusting the agitation speed and the temperature of the adsorption unit, the experiment begins and continues until the required time period is completed. After that, the unit is stopped automatically, and then the samples (glass test flasks) are carefully extracted and filtered first using Whatmann® 41 filter paper and then using a vacuum filtration kit, to completely remove the tangerine peels powder. Then, the resulting solution after treatment is examined by AAS and calibration curve to determine the efficiency and capacity of the adsorption, according to equation 1 and 2, respectively.

$$\%R = \frac{C_0 - C_f}{C_0} \times 100 \quad (1)$$

$$q \left(\frac{mg}{g} \right) = (C_0 - C_f) \frac{V}{m} \quad (2)$$

Where: %R: Percentage removal of tin(II) cations from tested contaminated aqueous solution, (dimensionless); q : Adsorbent capacity of tangerine peels, (mg/g); V : Volume of contaminated aqueous solution used in each experiment, (0.1 L); m : mass of adsorbent (tangerine peels) dosage used in the experiments, (0.5-6.5 g); C_0 and C_f : initial and final concentrations of tin(II) cations, (ppm).

3. EFFECTS OF OPERATIONAL FACTORS ON THE EFFICIENCY OF TIN(II) CATION REMOVAL USING TANGERINE PEELS

Influence of pH: The effect of changing the pH on the efficiency of removing tin(II) cations was studied within a range of 1-8, with all other operating parameters held constant at 300 rpm, 1 ppm, 1 g, 180 min, and 50 °C for the agitation speed, initial concentration of tin(II) cations, adsorption dose of tangerine peels, contact time, and temperature, respectively. The results obtained from studying this variable, as shown in Figure (3), indicated that the removal efficiency is very low at 3.06% at pH = 1, and gradually increases until it reaches a maximum value of 35.8% at pH = 5.5, then begins to decline sharply until it reaches 7.6% at pH = 8. Based on the above results, the removal efficiency is significantly affected by changes in the pH of the solution. At the initial three pH values (i.e. 1-3), the percentage removal of tin cations is very low. This may be due to insufficient required contact between the target cations and the surface of the adsorbent material (tangerine peels) to complete the treatment process. As the pH increases to 3.5 and then to 4, the treatment efficiency also increases in a semi-linear behavior. This is because the surface of the tangerine peels becomes able to capture a greater number of tin cations in the solution due to the increased negative charge (Ali et al., 2024b). This leads to repulsion between hydroxide anions (OH⁻) and an increased attraction for positively charged tin cations. This behavior continues until a pH of 5.5 is reached, where the treatment efficiency peaks, achieving the highest removal percentage of 35.8%. However, after exceeding this optimal pH, the treatment efficiency begins to decline dramatically, reaching 16.4% at a pH of 6.5. This result can be attributed to the

possibility of tin cations precipitating in an hydroxide form as a result of their reaction with the predominant hydroxide anions (OH⁻) in the solution, leading to the formation of insoluble compounds. Alternatively, the reduced ability of tangerine peels to adsorb tin(II) cations may be due to a change in the surface charge of the adsorbent or the formation of unstable complexes (Abdullah et al., 2023). This shows that the optimal value of the acid function of linseed peel as an adsorbent should not exceed 5.5 to achieve the best efficiency in recovering tin(II) cations from contaminated solutions.

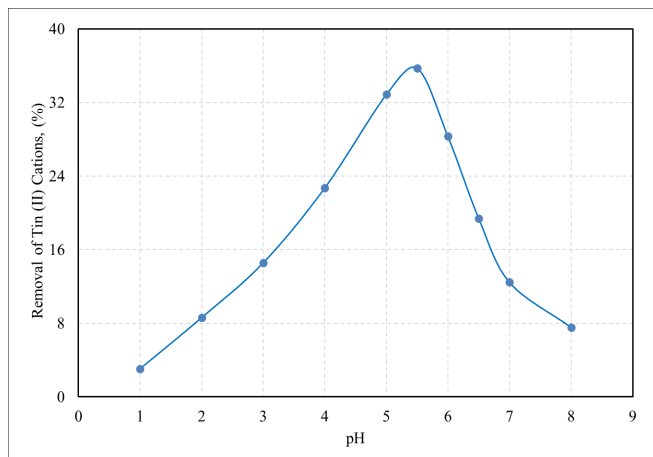


Figure 3: Influence of pH on tin(II) cations removal using tangerine peels

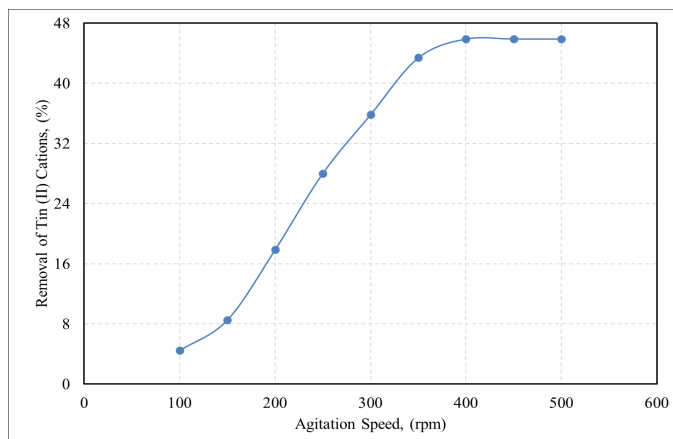


Figure 4: Effect of agitation speed on tin (II) cations removal using tangerine peels.

Effect of agitation speed: The effect of changing the agitation speed on the efficiency of removing tin(II) cations within a range of 100-500 rpm was studied, with the other operating parameters being kept constant at 5.5, 1 ppm, 1 g, 180 min, 50 °C for each of the pH function, initial concentration of tin(II) cations, adsorption dose of tangerine peels, contact time, and temperature, respectively. The results obtained from studying this variable, as shown in Figure 4, indicated that increasing the agitation speed leads to a gradual increase in the percentage removal of tin(II) cation until it reaches a certain limit, after which the efficiency becomes constant despite the continued increase in speed. At low speeds (100-150 rpm), the removal efficiency is very low, ranging between 4.25-8%. This can be explained by the fact that the agitation at these range is insufficient to ensure a homogeneous distribution of the adsorbent in the solution, leading to the precipitation of some of the peels and insufficient contact between the active sites of the adsorbent and the heavy metal cations in the solution (Abdullah et al., 2023). In addition, at low speeds, the effect of film boundary layer around the adsorption medium is greater, hindering the transfer of tin(II) cations to the surface of the adsorbent and thus reducing the adsorption rate. When the agitation speed increasing to between 300-350 rpm, a significant improvement in the percentage removal of tin(II) cation is observed, as the tangerine peels can capture between 35.84-43.41% of the total concentration of tin(II) cations in the contaminated aqueous solution, respectively. This indicates an improved distribution of the adsorption medium throughout the solution and a reduced effect of the film boundary layer, thus facilitating the transfer of tin (II) cations from the aqueous solution to the surface of the adsorbent material. Figure 4 shows that 46% is the highest percentage removal of tin

cations achieved at an agitation speed of 400 rpm, making this number the optimal value for the adsorption of the target ions. This indicates sufficient capture to achieve maximum removal of the contaminant from the solution. However, even with increased agitation speeds to 450 and 500 rpm, the efficiency did not improve and remained constant at 46%. This result could be attributed due to several factors. Firstly, most of the active sites on the surface of the tangerine peels are already saturated with the adsorbed heavy metal cations. This means that increasing the agitation speed beyond this value will not improve the removal percentage of target substance, as the material will no longer be able to adsorb any more tin(II) cations (Al-Hermizy et al., 2022). Secondly, very high speeds can create strong shear forces that break down the aggregates between the adsorbent molecules and reduce their stability. This can decrease the adsorption efficiency due to the instability of the adsorption medium within the aqueous solution (Ibrahim et al., 2021). On the other hand, high speeds can also lead to liberate of some adsorbed cations due to the effect of dynamic agitation forces, preventing the removal efficiency from improving further. Therefore, the results indicate that the optimal agitation speed for recovering tin (II) cations from contaminated solutions using tangerine peels as an adsorbent should not exceed 400 rpm.

Impact of initial concentration of tin(II) cations: The effect of changing the initial concentration on the efficiency of removing tin(II) cations within a range of 0.5-5 ppm was studied, with all other operating parameters held constant at 5.5, 400 rpm, 1 g, 180 min, 50 °C for each of the acidity function, agitation speed, adsorption dose of tangerine peels, contact time, and temperature, respectively. The results obtained from studying this variable, as shown in Figure 5, indicated that there is a complex relationship between the percentage removal, and the initial concentration of tin(II) cations. The relationship between them exhibits a clear dynamic that depends on the availability of adsorption sites on the surface of the tangerine peels and the effect of the concentration of tin(II) cations in the solution. Figure 5 shows that the removal efficiency reaches a maximum of 64% at a tin(II) initial concentration of 0.5 ppm, then gradually decreases with increasing the initial concentration to a minimum of 16.5% at an initial concentration of 5 ppm. The inverse relationship between treatment efficiency and initial concentration of pollutant can be explained by the availability of adsorption sites. Since the adsorption dose is constant, the surface area of the tangerine peels remains constant, meaning the number of surface sites available for adsorption on the treatment medium is also constant (Alsarayreh et al., 2024). When the initial concentration is low, the number of tin(II) cations in the solution is small, and the active sites are sufficient to capture a large number of target cations, resulting in high treatment efficiency. Conversely, increasing the initial concentration increases the number of tin (II) cations in contact with the surface of the tangerine peels, leading to competition among the pollutant ions for the same number of adsorption sites. As a result, the number of adsorbed cations will remain constant, but the number of unadsorbed cations will be greater as the concentration increases, and therefore the efficiency of the treatment will decrease. These results show that the performance of tangerine peels as an adsorbent is effective at low concentrations, but becomes limited at high concentrations due to gradual saturation, which means that the optimal initial concentration of tin(II) cations that achieves maximum efficiency of the studied adsorption medium is 4.5 ppm.

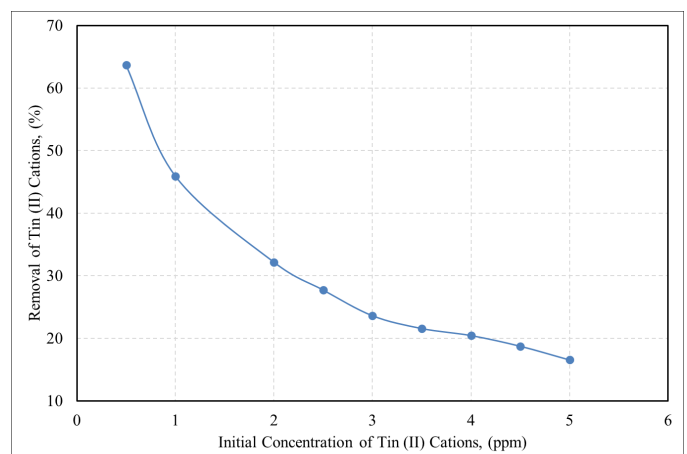


Figure 5: Impact of initial concentration on tin (II) cations removal using tangerine peels.

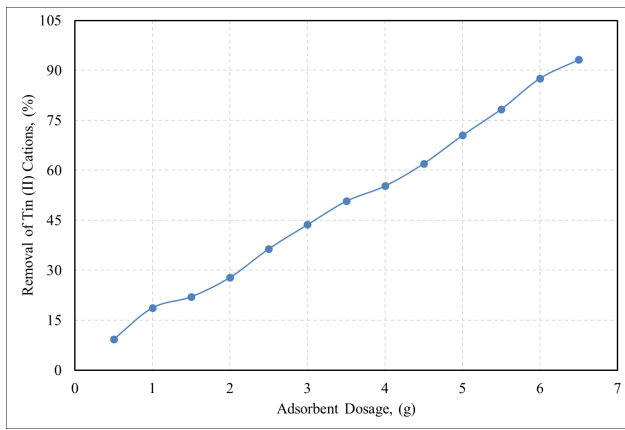


Figure 6: Potency of adsorbent dose on tin (II) cations removal using tangerine peels.

Potency of adsorbent dose: The potency of changing the adsorption dose of tangerine peels on the efficiency of removing tin(II) cations within a range of 0.5-6.5 g was studied, with the other operating parameters being kept constant at 5.5, 400 rpm, 4.5 ppm, 180 min, 50 °C for each of the acidity function, agitation speed, initial concentration of tin(II) cations, contact time, and temperature, respectively. The results obtained from studying this variable, as shown in Figure 6, indicated there is a direct relationship between increasing the adsorption dose of tangerine peels and the percentage removal of tin(II) cation. The initial percentage removal is 9.2%, achieved at a dose of 0.5 g of the adsorbent, and continues to rise gradually until it reaches 93.2% at a dose of 6 g of tangerine peels. After that, it remains constant at this value without change, even with the addition of further doses of tangerine peel. The explanation for this result is clearly related to the analysis of the result obtained from the initial concentration change. As the adsorption dose increases, the number of active sites capable of receiving tin (II) cations increases due to the increased surface area. The higher adsorption dose, means more target cations can be captured, as the relationship between the two variables is directly proportional (Alhamed et al., 2024b). The treatment process continues in this manner until the maximum treatment efficiency is reached at 6 g of tangerine peel, after which the percentage removal remains constant at 93.2% despite increasing the adsorption dose to 6.5 g. This result is attributed to the saturation process and the adsorption surface reaching an equilibrium state where the amount of tin(II) cations lost equals the amount adsorbed. Alternatively, the accumulation of the adsorbent in the same space may prevent the target cations from reaching the adsorption sites, and consequently, the adsorption efficiency remains constant at the maximum value. Furthermore, a balance between the number of tin(II) cations in the solution and the number of active sites available on the adsorption surface determines the maximum removal limit (Hameed & Abbas, 2024). When this limit is exceeded, increasing the dosage becomes ineffective because the concentration of the residual heavy metal in the solution falls to levels insufficient to occupy all the new sites provided by the adsorbent (Abbas et al., 2026). These results highlight that the optimal dose that achieves the highest adsorption efficiency without wasting the adsorbent is 6 g of tangerine peel, as increasing the dose after the saturation point will not lead to a significant improvement, and may be economically and practically ineffective due to the accumulation of solid matter and the increase in the viscosity of the contaminated aqueous solution, which may negatively affect the performance of the treatment process significantly.

Efficacy of contact time: The efficacy of changing the contact time on the efficiency of removing tin(II) cations within a range of 10-180 minutes was studied, with the other operating parameters being kept constant at 5.5, 400 rpm, 4.5 ppm, 6 g, and 50 °C for each of the acidity function, agitation speed, initial concentration of tin(II) cations, adsorption dose of tangerine peels, and temperature, respectively. The results obtained from studying this variable, as shown in Figure 7, indicated that there is a gradual increase in the removal percentage over time until it reaches an equilibrium point of 93.2% after 150 minutes. Initially, the removal percentage is very low, not exceeding 10% in the first 10 minutes. This can be explained by the fact that the tin(II) cations have not yet diffused

sufficiently to the surface of the tangerine peels, and that the interactions between the tin(II) cations and the active sites on the active adsorption surface have not yet reached their maximum levels (Alsarayreh et al., 2025a). After 45 minutes, the value of removal percentage increases to approximately 39%. Continuing the treatment process, the removal efficiency reaches 49%, then 73% after 60 and 120 minutes, respectively. Increasing the contact time provides a greater opportunity for tin(II) cations to reach the active sites on the surface of the tangerine peels, thus reducing the number of target cations in the solution and consequently increasing the treatment efficiency (Hasan et al., 2025). After two hours, the percentage of removal rises to 80%, then to its maximum value of 93.2% after 150 minutes, remaining constant even after the contact time is extended to three hours. The reason for the stability of the percentage of removal at the maximum value is that the adsorbent reaches saturation (under the specified operating conditions), at which point the surface of the tangerine peels can no longer accept any additional amount of tin (II) cations. In this state, adsorption is limited and not as rapid as in the previous periods, as most of the available active sites are filled and reach equilibrium (Alsarayreh et al., 2025b). These results indicate that the optimal contact time to ensure maximum tin (II) cation removal efficiency in the shortest possible time using tangerine peels is 2.5 hours.

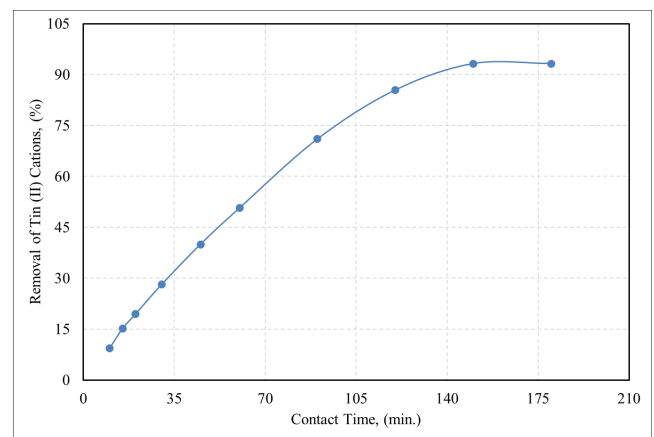


Figure 7: Efficacy of contact time on tin (II) cations removal using tangerine peels.

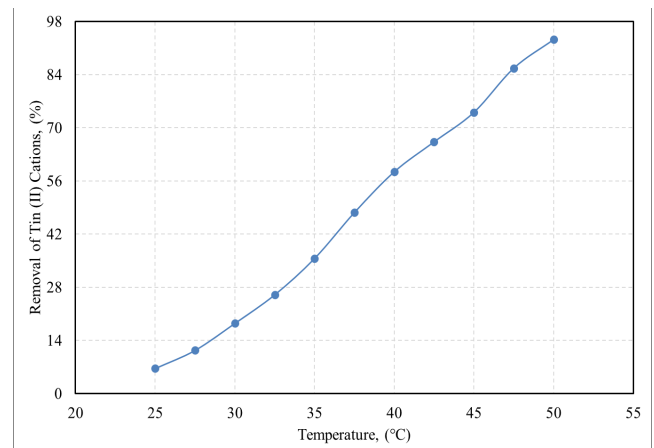


Figure 8: Performance of temperature on tin (II) cations removal using tangerine peels.

Performance of temperature: The performance of temperature variation on the removal efficiency of tin(II) cation was studied within a range of 25-50 °C, with all other operating parameters held constant at 5.5, 400 rpm, 4.5 ppm, 6 g, and 150 min for pH, agitation speed, initial tin(II) cation concentration, adsorption dose of tangerine peels, and contact time, respectively. The results obtained from studying this variable, as shown in Figure 8, indicate that the efficiency of the treatment clearly increases with increasing temperature, starting at laboratory temperature (25°C) with a very low removal rate not exceeding 7%, then gradually increasing with increasing temperature until it reaches 93.2% at 50°C. This phenomenon can be explained from the perspective of the effect of temperature on the physical and chemical adsorption processes occurring between tin (II)

cations and the surface of the adsorbed material from the tangerine peels (Al-Hermizy et al., 2025).

4. Characterization of Adsorbent Medium Before and After Treated with Tin (II) Cations Solutions.

The characterization of tangerine peels as an adsorbent for tin(II) cations was performed via X-ray diffraction (XRD) and X-ray fluorescent (XRF) analyses, as shown in Figure 9 and 10, respectively. These figures illustrated that the adsorbent material differ from clear changes due to treated with aqueous solutions contaminated by tin(II) cations. Moreover, it is clear that the adsorption is succussing, due to the pecks of tin (II) cations appears in Figures 9 and 10.

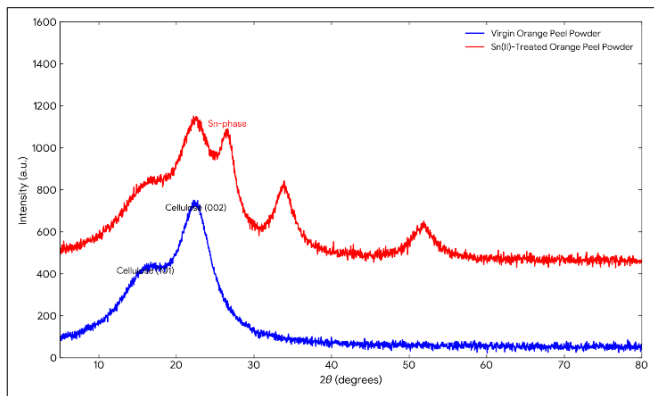


Figure 9: XRD analysis of tangerine peels before and after treatment with aqueous solutions contaminated by tin (II) cations.

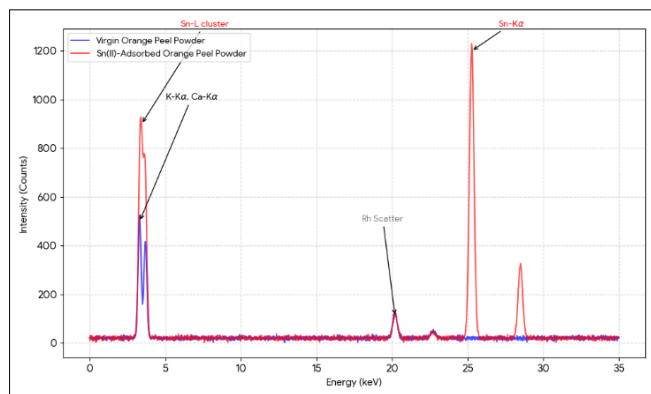


Figure 10: XRF analysis of tangerine peels before and after treatment with aqueous solutions contaminated by tin (II) cations.

5. CONCLUSIONS

Tangerine peels are often considered undesirable agricultural waste, but based on the concept of zero residue level (ZRL), their use as a biosorption medium for removing tin(II) cations, a hazardous heavy metal, was investigated. The results demonstrated the exceptional ability of aqueous tangerine peels to treat aqueous solutions contaminated with tin(II) cations under various operating conditions in a batch-type adsorption unit. After 2.5 hours of treatment, 60 g/L of the peels was able to remove more than 93% of the tin(II) cations at concentrations 150% higher than the maximum acceptable limit in drinking water, at a pH close to neutral, an agitation speed of 400 rpm, and a temperature of 50°C. These results confirm that agricultural waste in general, and tangerine peels in particular, represent a sustainable source for water treatment, transforming them from an environmental burden to be disposed of into a valuable and significant resource. Given these outcomes, a more in-depth study is required to investigate the suitability of this material for treating actual wastewater contaminated with heavy metals and organic materials.

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