Heliyon 11 (2025) e42281

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Efficient removal of lead (II) from paint factory wastewater using Noug stalk activated carbon: A sustainable adsorption approach

Getasew Yirdaw

Department of Environmental Health Science, College of Medicine and Health Sciences, Debre Markos University, P.O Box 269, Debre Markos, Ethiopia

ARTICLE INFO

Keywords:
Adaptability
Lead (II)
Noug stalk activated carbon
Paint factory
Wastewater

ABSTRACT

Industries are among the largest global consumers of water, with a significant portion being converted into industrial wastewater. Paint factories, in particular, are major contributors to environmental lead pollution, releasing lead (II) through untreated effluents. Exposure to lead (II) poses serious health risks, including carcinogenic effects, neurological disorders, blood-related complications, and damage to vital organs such as the liver, kidneys, and lungs. While extensive research has focused on lead (II) removal from synthetic wastewater, limited studies have addressed the application of these methods to real industrial wastewater. This study aimed to evaluate the efficiency of Noug stalk activated carbon in removing lead (II) from paint factory effluent under optimized conditions. Laboratory experiments were conducted to assess the performance of Noug stalk activated carbon in treating wastewater from a paint factory. Statistical analysis using Statistical Package for Social Sciences version 20 was employed, with a paired sample *t*-test determining the significance of differences in lead (II) concentrations before and after treatment, considering a p-value of <0.05 as statistically significant. The paint factory wastewater sample exhibited a pH of 6.62, temperature of 20.40 °C, chemical oxygen demand of 1717 mg/L, total suspended solids of 710 mg/L, total dissolved solids of 1231 mg/L, and a lead (II) concentration of 23.54 mg/L. Results demonstrated a lead (II) removal efficiency of 94.84 %, with a significant reduction in lead (II) concentration post-treatment ($t = 157.62$, $p < 0.001$). These findings highlight the potential of Noug stalk activated carbon as an effective adsorbent for real industrial wastewater treatment. Further research is necessary to explore how the presence of other heavy metals may affect its performance and to investigate column adsorption techniques and regeneration processes after depletion.

1. Introduction

Humans depend on water for their lives, necessitating its considerable use, which eventually generates waste products called wastewater. Industries are the largest water users, with a substantial portion of it becoming industrial wastewater [1,2]. In the past few decades, increased pressure exerted by anthropogenic actions, rapid urbanization, and industrialization has led to massive degradation of aquatic environments, directly or otherwise, impacting human health [3,4]. The environmental status of aquatic ecosystems is often a reflection of how degraded the environment has become, impacting both the quality of water and the gain from the environment [5]. However, only 20 % of all wastewater in the world is treated to acceptable levels before being re-introduced into the environment [6].

E-mail address: getasew_yirdaw@dmu.edu.et.

https://doi.org/10.1016/j.heliyon.2025.e42281
Received 27 June 2024; Received in revised form 29 November 2024; Accepted 24 January 2025
Available online 25 January 2025

High-income countries treat this water to a higher acceptable standard compared to low- and middle-income countries [7].

Surface water bodies nearer to factory setups receive large volumes of toxic waste yearly, further worsening the pollution state [8]. Most countries, including Ethiopia, treat only a portion (10 %) of water produced by their industries. Instead, the remaining volumes (90 %) are left untreated and directed into adjacent rivers [9]. Ethiopia, along with other regions globally, has implemented policies supporting the development of both small and large-scale industries. Consequently, there is a notable surge in the number of industries, directly or indirectly utilizing lead (Pb (II)) [10]. Although the year 2000 marked the beginning of banning leaded petroleum fuel usage in most countries, the paint industry significantly contributes to contamination [11]. The wastewater from paint industries carries a significant amount of organic materials and various harmful inorganic substances, including Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Dissolved Solids (TDS), turbidity, colored compounds, and heavy metals [12], with Pb(II) being among them. Lead is produced for multiple uses in the paint factories. It is used to improve the color of the paint and facilitate the catalyzation of chemical reactions. Purification of the products leads to waste, which is expelled into the water bodies [13,14].

In Ethiopia, there are more than 37 operational paint factories [15], serving as the primary contributors to environmental lead pollution [16,17]. The majority of these Ethiopian paint facilities, including the Kokeb paint factory, employ lead and release untreated wastewater directly into nearby water sources [9,18]. Such practices lead to the accumulation of Pb(II), resulting in severe reverberation on aquatic ecosystems and public health. Such effects arise from lead's toxic properties; even low levels can pose serious health risks, resulting in various severe conditions, including cancer, neurological disorders, blood-related issues, and harm to vital organs [19,20]. Ethiopia is already grappling with the tangible effects of water pollution stemming from paint manufacturing [21], underscoring the urgent need to address this issue to safeguard both aquatic ecosystems and human well-being.

In recent years, the demand for effective and affordable methods to remove Pb(II) from contaminated water has increased. Adsorption has emerged as the preferred technique due to its cost-effectiveness and efficiency in removing metal ions, particularly in economically challenged countries like Ethiopia [22,23]. While adsorption using ring- and ligand-based adsorbents [24–33] offers a selective method for removing heavy metals and contaminants from wastewater, these materials tend to be more expensive to synthesize. Their production requires specialized chemicals and processes, which can make them less feasible for large-scale or resource-limited applications. Additionally, the synthesis of these adsorbents often involves complex reactions that may produce hazardous by-products, raising concerns about environmental and safety impacts.

In contrast, research has explored the use of activated carbons derived from various agricultural residues such as teff stalk [34], maize stalk & tassel [35,36], rice husk [37], peanut shell [38], corncob waste [39], sugarcane bagasse [40], date palm [41], lemon peel [42], grape wood [43], and sunflower stalk [44], for Pb(II) removal from wastewater. Such activated carbon options derived from other agro-waste face availability and cost constraints for treating wastewater containing Pb(II) [22,23]. Porous carbon emanating from Noug stalk faces no issues related to availability and cost due to its lack of value for hog feeding and other purposes [22]. NSAC was selected as an adsorbent for Pb(II) removal due to its demonstrated effectiveness, featuring a BET surface area of 473.45 m^2/g, a yield of 53.78 %, an iodine number of 576.00 mg/g, a porosity of 67.50 %, and a bulk density of 0.37 g/cm^3 [22]. It also achieved a removal efficiency of 98.77 % from aqueous solutions [23]. These materials are abundant, renewable, and inexpensive, making them attractive candidates for sustainable water treatment. The process of converting these agricultural residues into activated carbon involves chemical activation, which enhances their surface area and porosity, allowing for the effective adsorption of metal ions.

Despite the promising results from previous research [35,36,45,46], most studies have focused on the removal of Pb(II) from synthetic wastewater, which does not fully reflect the complexity of real industrial wastewater. Synthetic wastewater is often devoid of the competitive ions and organic matter that are typically present in industrial effluents, meaning that the applicability of these findings to real-world scenarios remains limited. Real industrial wastewater presents a much more complex challenge due to the presence of multiple pollutants that can compete with lead for adsorption sites on activated carbon. As a result, the effectiveness of agricultural residues as adsorbents for Pb(II) removal in actual industrial settings remains largely unexplored.

In response to this gap in the research, our study was aims to investigate the potential of Noug (Guizotia abyssinica Cass.) stalk as an adsorbent for the removal of Pb(II) from real industrial wastewater. Noug (Guizotia abyssinica Cass.) stalk, a commonly cultivated cereal crop in Ethiopia, emerges as a promising solution as a low-cost agricultural by-product for producing porous carbon used in Pb (II) removal from polluted wastewater [22,23]. Previous research has showcased the effectiveness of Noug stalk activated carbon (NSAC) in removing Pb(II) from synthetic wastewater under optimized conditions [23]. Hence, this study seeks to evaluate the efficiency of NSAC in purging Pb(II) from genuine industrial (paint) wastewater under ideal conditions. Such an approach is deemed optimal for up scaling the technique for widespread application within the wastewater treatment industry.

2. Methods and materials

2.1. Study design, area, and period

An experimental investigation was carried out in the laboratory between April and June 2023. The actual industrial wastewater used in the study was sourced from the Kokeb paint factory. Kokeb paint Factory is one of the paint factories in Ethiopia, found in Bahir Dar town. It has an annual production capacity of processing 35 million liters of paint. The factory generates a large amount of wastewater every day and dumps it directly into the Abay (Nile) River without an advanced treatment to remove its lead content.

2.2. Preparation of porous carbon using Noug stalk

The preparation of Noug stalk activated carbon (NSAC) followed procedures outlined in our prior studies [22,23]. Noug stalk, an eco-friendly agricultural byproduct readily available in the vicinity, served as the raw material for NSAC production. Procured from local farmers, the stalks were carefully gathered in clean polyethylene bags, washed with distilled water, and sun-dried. They were then oven-dried at 105 °C for 24 h to eliminate excess moisture. Next, the dried stalks underwent mixing with concentrated H_3PO_4 at a ratio of 1:2 w/w% and were left to stand at room temperature for 24 h. Following this, the residual material was washed with distilled water and soaked in a 2 % $NaHCO_3$ solution for a full day for equilibration. The resultant material was naturally air-dried before undergoing further drying in a hot oven at 105 °C for 24 h. Subsequently, it was subjected to a muffle furnace at 537.50 °C for 127 min. The resulting porous carbon was finely ground into particles measuring 1–2 mm and stored in desiccators for subsequent use.

2.3. Sample size determination and sampling procedure

To determine the adaptability of the technique to industrial wastewater, a total of 54 samples were collected. The sample size was calculated using the formula proposed by Manly Bryan [47] using the equation as follows (see Eq. (1)):

$$n = \frac{4\sigma^2}{\delta^2} \quad \text{Eq. 1}$$

where n is the number of samples, σ is the standard deviation, and δ is the acceptable level of error. Eight (8) samples of paint factory effluent were collected for pretesting, each with triplicate readings, revealing a standard deviation of 0.099. An acceptable level of error of 2.7 % was chosen, and the total sample size was calculated to be 54. To collect the samples, three grab samples were taken at different times of the day (morning, mid-day, and afternoon) for 18 days a month from Kokeb paint factory effluent at the point of discharge of the wastewater.

2.4. Sample collection and characterization of paint wastewater

Wastewater samples from the Kokeb Paint factory underwent collection and analysis to ascertain the levels of Pb(II), pH, electrical conductivity (EC), total dissolved solids (TDS), chemical oxygen demand (COD), total suspended solids (TSS), and temperature. Standard protocols for water and wastewater examination were strictly adhered to during the analysis process [48].

Lead (II) concentrations were assessed utilizing a Flame atomic absorption spectrometer (FAAS), while the pH of the sample was gauged employing the Direct Reading Engineering Method (DREM) using a pH meter. For pH determination, the meter probe was submerged in a 50 mL beaker filled with the effluent sample, and the pH mode was activated. The displayed reading was recorded as the actual pH value. On-site temperature readings were obtained using a digital thermometer.

Total dissolved solids (TDS) and Electrical Conductivity (EC) are widely acknowledged indicators of the various ionized components present in water, directly reflecting the combined presence of cations or anions as determined through chemical analysis. EC typically correlates with the overall salt concentration. In this study, both TDS and EC were measured using a Jenway model 4510 conductivity/TDS meter. For each measurement, the meter's probe was submerged in a 50 mL beaker containing the effluent sample, and the TDS and EC mode was activated to determine the total dissolved solids and electrical conductivity, respectively. The displayed readings were recorded as accurate TDS and EC values.

Total suspended solids (TSS) were assessed through the gravimetric approach. Initially, a porcelain crucible underwent drying in an oven at 100 °C until it reached a consistent weight (W1). Subsequently, a 50 mL portion of the paint effluent sample was introduced into the crucible, and the crucible was subjected to heating in the oven at 100 °C until the effluent evaporated. Following cooling in a desiccator, the crucible was reweighed to determine the weight (W2). The total suspended solids were then calculated using the provided equation (see Eq. (2)):

$$\text{Total Suspended Solid, TSS (mg / L)} = \frac{(\text{W2} - \text{W1}) \text{ x } 100}{50 \text{ mL}} \quad \text{Eq. 2}$$

where W2 is the weight of the sample after heating in an oven at 100 °C, W1 is the initial weight of the sample before heating, and 50 mL is the volume of the sample (paint effluent).

Chemical oxygen demand (COD) quantifies the oxygen utilized in chemically oxidizing pollutants within wastewater. It gauges the oxygen required to oxidize the organic substances within a wastewater sample under defined conditions of oxidizing agent, temperature, and duration [49]. Take 2.50 mL of wastewater sample and another 2.50 mL of distilled water in separate tubes. Add 1.50 mL of potassium dichromate to both tubes, resulting in a yellow coloration. Then, cautiously introduce 3.50 mL of sulfuric acid reagent into each tube, seal them tightly, and place them in a COD digester set at 150 °C for 2 h. After cooling to room temperature, transfer the contents to a conical flask. Fill a burette with freshly prepared ferrous ammonium sulfate and add a drop of ferroin indicator to the conical flask, producing a green hue. Titrate the content against ammonium sulfate until the color changes to reddish-brown, and then calculate the COD concentration as follows (see Eq. (3)):

$$\text{Chemical Oxygen Demand, COD (mg / L)} = \frac{(\text{A} - \text{B}) \text{ x N x } 8000}{\text{Vol. of Sample}} \quad \text{Eq. 3}$$

where A is the volume of the blank titrant, B is the volume of the sample titrant, and N is the normality of ferrous ammonium sulfate (FAS).

2.5. Application of NSAC to the treatment of industrial wastewater

The versatility of the method utilizing Noug stalk activated carbon for the removal of Pb(II) was tested using real effluent samples. Specifically, wastewater from the paint factory was gathered directly from the discharge site at the Kokeb paint factory.

2.5.1. Wastewater sampling

In order to assess NSAC's suitability for effectively eliminating Pb(II) from genuine industrial wastewater, a 1000 mL combined sample of wastewater was obtained from the discharge of Kokeb paint factory using a polyethylene bottle that had undergone cleaning with 10 % v/v HNO_3 followed by rinsing with distilled water.

2.5.2. Adsorption from wastewater

The wastewater underwent treatment with NSAC under optimal conditions (pH = 4.87, adsorbent dose = 18.43 g/L, and contact time = 2.04 h), with agitation at a speed of 200 rpm at 25 °C [23]. Subsequently, the samples were filtered using Whatman No.1 filter paper, and the filtrate was digested for further analysis.

2.5.3. Acid digestion of wastewater

The digestion process for both NSAC-treated and untreated wastewater samples involved transferring a measured volume (50 mL) of well-mixed water sample preserved with acid into a flask. Next, 5 mL of concentrated HNO_3 and a few boiling chips were introduced into the flask, and the mixture was boiled and evaporated on a hot plate until the volume was reduced to its minimum (10–20 mL). Further heating and the gradual addition of concentrated HNO_3 were conducted as required until complete digestion was achieved, indicated by a clear solution of light color. Care was taken to prevent the sample from drying out during digestion. After digestion, the flasks were rinsed with water and filtered. The resulting filtrate was then transferred into a 50 mL volumetric flask, diluted to the mark, and thoroughly mixed. A portion of this solution was extracted for the necessary metal determinations [6].

2.5.4. Analysis using flame atomic absorption spectrophotometer

FAAS was selected as the method for determining the concentration of Pb(II) in the sample due to its recognized reliability and precision in measuring heavy metals specifically, Pb(II) concentrations. All samples were processed in triplicate under identical conditions, and the average results were recorded. The percentage of Pb(II) removal was computed using the formula [23];

$$\text{Removal Efficiency } (\%) = \frac{(\text{Co} - \text{Ct}) \quad \text{x} \quad 100}{\text{Co}} \qquad \text{Eq. 4}$$

where, Co - initial concentration of Pb(II) in mg/L, and Ct – concentration of Pb(II) in mg/L at a given time, t.

2.6. Data processing and statistical analysis

The data were inputted and analyzed utilizing SPSS version 20 statistical software. Frequency and percentage distributions were utilized to present most variables. Descriptive analysis was employed to illustrate the mean and standard deviation of Pb(II) levels before and after treatment of the wastewater with NSAC under optimized process conditions. A paired *t*-test was conducted to examine whether a significant difference existed in the mean concentration of Pb(II) before and after treatment, indicating the efficacy of NSAC in Pb(II) removal. A significance level of $p < 0.05$ was established as the threshold for identifying a statistically significant mean difference. The efficiency of NSAC in Pb(II) removal was subsequently determined based on the mean Pb(II) concentration before and after treatment.

2.7. Data quality control

The chemical reagents used in the study underwent standardization procedures. In this study, we conducted multiple tests (triplicate readings) for each sample of wastewater characterization and adsorption using NSAC to ensure the validity of our results. Calibration of the FAAS involved the use of seven standard Pb(II) solutions ranging from 0 to 12 ppm. A calibration curve was then generated by plotting the absorbance against the concentration of Pb(II), and sample analysis was carried out when the correlation coefficient exceeded 0.99 (99 %) (See Annex I of the Supplementary Material file). Reproducibility was ensured by conducting triplicate analyses and measurements for each sample. Additionally, the recovery percentage was employed as a quality control measure to assess the reliability of both the digestion method and the measuring instruments.

3. Results and discussion

3.1. Characterization of paint factory effluent

Drawing from our previous studies, NSAC has been developed, analyzed, and optimized specifically for the efficient extraction of Pb (II) from synthetic wastewater. Referring to our previous publication provides a comprehensive insight into the characteristics of the adsorbent [22,23].

The pH level of wastewater indicates its ability to neutralize acidic or basic conditions. The mean pH value of the effluent was recorded at 6.62 ± 0.74, suggesting a slightly acidic nature that is nearing neutrality. This aligns with the WHO's acceptable range of 6–9 [21]. In comparison with other paint factories in Ethiopia like Kadisco (6.77), and Bright (6.48), our findings were almost in line [21]. Specifically, our result was higher than that of Nifas Silk (5.30) [50] and lower than Zemillic (7.16), Rainbow (7.70) [21], Gast Solar (10.95), and Modern Industry (8.41) [17].

Water's electrical conductivity indicates its capacity to conduct electric current, which hinges on ion presence, its overall concentration, mobility, and water temperature. This parameter serves as a crucial determinant of water suitability for irrigation and provides insights into wastewater salinity or total salt content [3]. The untreated wastewater demonstrated an electrical conductivity of 259,617 ± 12.6 μS/m, aligning with WHO guidelines [17]. This value exceeds those recorded in certain paint factories like Kadisco (35,264 μS/m), Gast Solar (154,688 μS/m), Zemillic (201,536 μS/m), and Modern Industry (202,816 μS/m), yet falls below figures from Nifas Silk (351,744 μS/m) and Rainbow (432,576 μS/m) [17].

Temperature is one of the most important parameters in water and wastewater samples. In this study, the temperature of the wastewater effluent was 20.40 ± 1.75 °C. This result is congruent with the recommended WHO permissible level [50]. The result of the study was lower than the value reported in the Nifas Silk paint factory (20.60 °C), Ethiopia [50].

Chemical oxygen demand (COD) serves as a crucial indicator of industrial effluent pollution levels, signaling the extent of pollutants present. In our investigation, the average COD of the paint factory effluent measured at 1717 ± 5.65 mg/L, exceeding the WHO's permissible limit of 120 mg/L [50]. This elevation may be attributed to the substantial presence of toxic substances in the effluent. Our findings surpass the COD values reported in various paint factories such as Gast Solar (140 mg/L), Rainbow (270 mg/L), Zemillic (340 mg/L) [17], and Kadisco (425 mg/L) [21]. However, they fall short of those documented in Nifas Silk (2190 mg/L), Modern Industry (2670 mg/L), Bright (2887.20 mg/L), Rainbow (7662.50 mg/L), Zemillic (3524 mg/L) [21], and Nifas Silk (2402 mg/L) [17].

In this study, the concentration of total suspended solids was measured at 710 ± 3.25 mg/L, surpassing the WHO's designated permissible threshold of 45 mg/L [50]. Our findings exceed those reported in various paint factories including Gast Solar (55 mg/L), Kadisco (63 mg/L), Rainbow (80 mg/L), Zemillie (205 mg/L), and Modern Industry (418 mg/L) [17], as well as Nifas Silk (619 mg/L) [50]. However, they fall short of the levels observed in Nifas Silk (1980 mg/L) [17].

Total dissolved solids (TDS) represent the sum of inorganic salts and other substances dissolved within water. Effluents with elevated TDS levels pose potential salinity concerns if discharged into irrigation water [17]. This study found that the concentration of total dissolved solids in the paint effluent was recorded at 1231 ± 7.23 mg/L, surpassing the WHO's acceptable limit of 500 mg/L for discharge into drinking water sources and consistent with the Ethiopian Standard (ES) threshold of 3000 mg/L [17]. However, our findings exceed those reported in various paint factories such as Kadisco (501.10 mg/L), Zemillie (284.90 mg/L), Nifas Silk (475.70 mg/L), and Rainbow (615.20 mg/L), yet remain lower than those of Gast Solar (2207 mg/L) and Modern Industry (2883 mg/L) [17].

The mean concentration of Pb(II) in the effluent measured at 24.65 ± 0.91 ppm closely resembled the levels detected in the Zemillic paint factory in Ethiopia [21]. However, it exceeded results from Nifas Silk (8.33 ppm), Cadisco (0.68 ppm), and Bright (18.73 ppm) [21], as well as general reports on paint industry effluents in Ethiopia [17], and Nifas Silk (4.60 ppm) [50]. Conversely, it was lower than findings from Rainbow Paint Factory (53.40 ppm) [21]. Nevertheless, this concentration significantly surpasses the WHO's recommended discharge level of Pb(II) into the environment, set at 0.01 ppm [17]. Such elevated Pb(II) discharge poses severe health risks to humans and other organisms, even at low concentrations, leading to adverse effects [19,51]. This underscores the necessity for additional treatment to mitigate toxic Pb(II) ion in the effluent prior to discharge into the environment (Refer to Table 1).

3.2. Application of NSAC onto real industrial wastewater

After subjecting the effluent to treatment with NSAC under optimized conditions, the average Pb(II) concentration reduced from 24.65 ppm to 1.27 ppm (refer to Table 2 and Fig. 1). However, this value still exceeds the permissible limit of Pb(II) concentration (0.5

Table 1
The Laboratory examination findings from real wastewater samples collected at Kokeb Paint Factory, Ethiopia, 2023 (n = 54).

Parameters	Unit	Number of samples	Concentration (mean±SD)
Pb(II)	ppm	54	24.65 ± 0.91
Temperature	°C	54	20.40 ± 1.75
pH	–	54	6.62 ± 0.74
Electrical Conductivity (EC)	μS/m	54	259,617 ± 12.60
Chemical Oxygen Demand	mg/L	54	1717 ± 5.65
Total Suspended Solids (TSS)	mg/L	54	710 ± 3.25
Total Dissolved Solids (TDS)	mg/L	54	1231 ± 7.23

Table 2
Utilization of NSAC as an adsorbent for eliminating Pb(II) from real industrial wastewater under conditions of pH 4.87, adsorbent dosage of 18.43 g/L, contact duration of 2.04 h, agitation at 200 rpm, and temperature of 25 °C (n = 54).

Conc. Of Pb(II) (ppm)	N	Maximum	Minimum	Mean	Std. deviation
Before treatment with NSAC	54	24.05	22.91	24.65	0.91
After treatment with NSAC	54	1.30	1.20	1.27	0.52

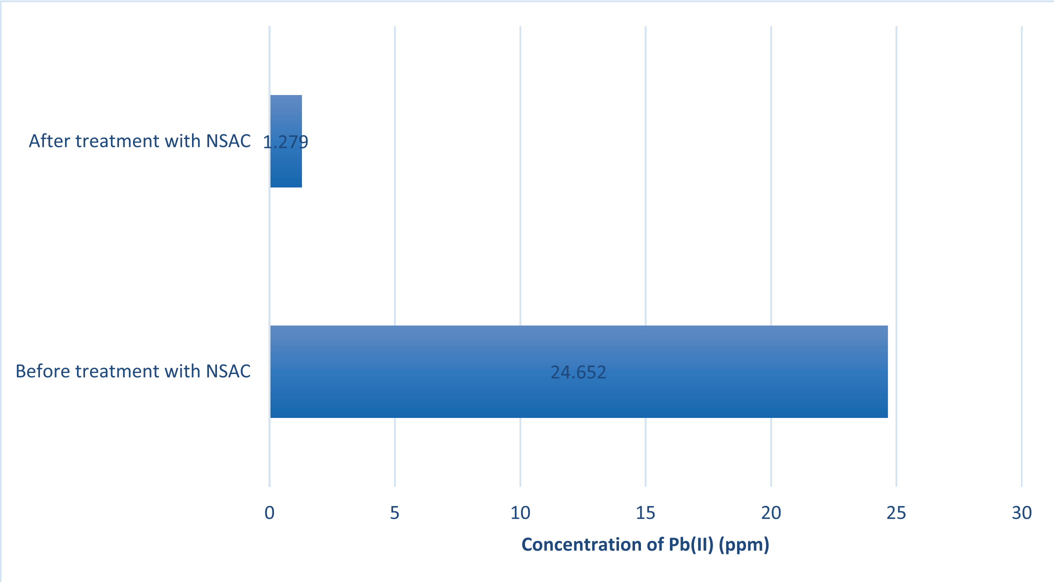

Fig. 1. Lead (II) concentration in paint effluent before and following treatment with NSAC.

ppm) set by the Ethiopian Environmental Protection Authority (EEPA) [18], and WHO (0.01 ppm) [17] for direct discharge of paint wastewater into the environment.

NSAC exhibited superior efficiency in removing Pb(II) compared to the current treatment method. Thus, utilizing Noug stalk activated carbon for treating discharge effluents is recommended, as it can reduce over 94.84 % of Pb(II), safeguarding human health, aquatic ecosystems, and the environment overall (refer to Table 2).

The paired *t*-test results indicated a significant disparity in the mean concentration of Pb(II) before and after NSAC treatment, with $t = 157.62$ and a $p\text{-value} < 0.001$ (refer to Table 3). The higher t value (157.62) signifies a substantial distinction between the two groups, surpassing the critical t value. With a p-value below 0.001, the null hypothesis was dismissed in favor of the alternative hypothesis, confirming a significant difference between the observed groups (before and after treatment with NSAC). This suggests that NSAC served as an effective adsorbent for removing Pb(II) from real wastewater, significantly reducing its concentration. The removal efficiency was measured at 94.84 %, consistent with findings from studies employing biomass-based activated carbons like arundinaria alpina stem [52], tea waste, and peanut shell [38,53].

3.3. Significance of employing NSAC for the elimination of lead (II)

Based on the findings of this study, employing Noug stalk activated carbon in real industrial wastewater can eliminate over 94.84 % of Pb(II). This indicates its potential to substantially mitigate diseases and environmental harm caused by lead pollution, serving as a

Table 3
The outcome of a paired sample *t*-test conducted on the utilization of NSAC for eliminating Pb(II) from industrial effluent under conditions of pH 4.87, an adsorbent dosage of 18.43 g/L, contact duration of 2.04 h, agitation at 200 rpm, and a temperature of 25 °C.

Pb(II) before treatment & Pb(II) after treatment							
Paired differences							
			95 % CI of difference				
Mean	Std. deviation	Std. error mean	Lower	Upper	t value	df	Sig. (2 – tailed)
22.28	0.63	0.09	22.05	22.74	157.62	53	0.000

preventive measure to safeguard both human health and the environment. Industries are encouraged to adopt the use of NSAC for removing toxic heavy metals like Pb(II) from industrial wastewater, aligning with legal regulations aimed at protecting human health and the environment.

3.4. Comparison of NSAC versus other agro-waste based activated carbons

The removal efficiency of Pb(II) using Noug stalk activated carbon (NSAC) is fairly comparable to that of other activated carbons made from agro-waste, such as those from peanut shells, as indicated in Table 4. However, NSAC demonstrated a lower removal efficiency for Pb(II) than certain other agro-waste-based activated carbons, including those from cassava peel, rice husk, and sunflower seed and stalk, while outperforming lemon peel and date palm. Differences in removal efficiency might arise from variations in the composition of functional groups among adsorbents, as well as variances in preparation methods and the conditions of application, both in synthetic wastewater and in actual industrial effluent. Additionally, NSAC's removal efficiency was lower than its performance in synthetic wastewater [23], possibly due to the presence of competitive ions and other matrices diminishing its effectiveness as an adsorbent.

3.5. Recovery percent as quality control

The percentage of recovery served as a quality control measure to assess the efficiency of both the digestion method and the measuring instruments. The recovery percentage was determined to be approximately 96.31 % (refer to Table 5). This suggests that the digestion method and measuring instruments retained 96.31 % of the Pb(II) present in the sample; only 3.6 % might have been overlooked or lost during digestion [57]. Hence, the findings of this experiment are deemed accurate, and the generated data are considered credible.

3.6. Desorption studies

The regeneration of NSAC was carried out by immersing it in a 1 M concentrated phosphoric acid (85 % w/w) for 1 h. Following this, the NSAC was filtered, thoroughly rinsed with distilled water, and dried in an oven at 105 °C for 24 h. The regenerated NSAC was then tested for its reusability by applying it to a real paint industry wastewater sample under specific conditions: an adsorbent dose of 18.43 g/L, a contact time of 2.04 h, an agitation speed of 200 rpm, and a temperature of 25 °C. The reusability performance, summarized in Table 6, revealed a gradual decline in lead ion removal efficiency over the first, second, third, and fourth reuses cycles. This reduction is likely due to decreased active site availability and pore blockage in the NSAC [58,59]. These findings suggest that in acidic conditions, protons effectively displace significant amounts of adsorbed lead by competing with Pb(II) ions for adsorption sites. The results align well with observations reported in previous studies [60,61].

3.7. Health Implication

Lead enters aquatic ecosystems through the discharge of untreated industrial effluents, becoming biomagnified within the food chain and posing significant public health concerns [20]. Numerous studies have evaluated the health risks associated with Pb(II) exposure via various pathways, including drinking contaminated water, inhaling lead-laden dust, dermal contact with polluted soil and water, and consuming crops grown in contaminated environments [62]. Crops such as rice, wheat, potatoes, and vegetables cultivated with lead-polluted water from industrial discharges often accumulate high levels of lead, leading to severe health risks [63,64].

In this study, the prepared NSAC demonstrated the ability to remove 94.84 % of Pb(II) from wastewater, effectively bringing lead concentrations within the WHO's permissible discharge limits for industrial effluents. These findings suggest that using this treatment method can significantly reduce health risks associated with industrial lead pollution.

Table 4
Removal efficiency of different agro waste based activated carbon.

Activated carbon	Activation method	Type of wastewater	Removal efficiency (%)	Reference
Noug stalk	Chemical activation	Industrial (real)	94. 81	This work
Noug stalk	≫	Synthetic (aqueous)	98.77	[23]
Lemon peel	≫	≫	89.16	[42]
Date palm	≫	≫	92.00	[41]
Cassava Peel	≫	≫	96.83	[54]
Rice husk	≫	≫	96.72	[55]
Sunflower seed	≫	≫	99.61	[56]
Sunflower stalk	≫	≫	97.00	[44]
Peanut shell	≫	≫	95 %	[38]

Table 5
Recovery tests for the optimized procedure of wastewater sample.

Instruments used	Sample	Conc. in unspiked sample (ppm)	Amount added (ppm)	Conc. in spiked sample (ppm)	Mean %Recovery
FAAS	Untreated wastewater	24.59 ± 0.08	5.00	29.30 ± 0.08	96.31
	Treated with NSAC	1.24 ± 0.06	5.00	6.16 ± 0.06	

Table 6
Regeneration of NSAC at an adsorbent dose of 18.43 g/L, a contact time of 2.04 h, and an agitation speed of 200 rpm at room temperature (25 °C) in a 100 mL paint industry wastewater sample.

Cycle of reuse	Lead (II) removal efficiency (%)
1st	94.84 %
2nd	82.71 %
3rd	69.45 %
4th	47.92 %

4. Limitations of the study

In this research, adsorption was performed in a batch adsorption mode due to the study's limited duration, instead of employing the column adsorption process, which is more suitable for industrial design. As the sample was obtained from a single industry, it may not fully represent the characteristics of paint factory effluent in Ethiopia. A sampling procedure involving the collection of composite samples over various periods and seasons was not implemented to obtain a more accurate and comprehensive representation of paint factory effluents. Another key limitation of this study is the absence of an examination of regeneration and recovery processes for the adsorbents used. The ability to regenerate and reuse these materials is critical for effective heavy metal removal, as it significantly impacts the cost-effectiveness of wastewater treatment technologies. Implementing these practices allows industries to recover concentrated Pb(II) from the adsorbents, which is essential for minimizing the costs of sourcing raw materials (such as lead) for future production. Furthermore, this approach provides a waste management solution, reducing the environmental and health risks associated with adsorbed Pb(II) in humans, plants, and ecosystems. Therefore, it is important for future researchers to address this issue.

5. Conclusions

In conclusion, this study demonstrates the potential of Noug Stalk Activated Carbon (NSAC) as an innovative, sustainable, and cost-effective adsorbent for the efficient removal of Pb(II) from real industrial wastewater. Analysis of wastewater samples from the paint factory revealed key characteristics, including a pH of 6.62, a temperature of 20.40 °C, a chemical oxygen demand of 1717 mg/L, total suspended solids of 710 mg/L, total dissolved solids of 1231 mg/L, and a Pb(II) concentration of 23.54 mg/L. The application of NSAC achieved an impressive Pb(II) removal efficiency of 94.84 %, with a statistically significant reduction in Pb(II) concentration before and after treatment ($t = 157.62$, $p < 0.001$).

These findings highlight NSAC's efficiency as an eco-friendly alternative to conventional adsorbents, aligning with prior research on the use of agricultural by-products for wastewater treatment. However, the complexity of real industrial effluents, often containing multiple heavy metals, warrants further exploration of NSAC's performance in such conditions. Future studies should also focus on optimizing the regeneration and reuse of NSAC to enhance its sustainability and practical applicability. Overall, this research provides valuable insights into the use of agricultural waste for environmental remediation and offers a promising approach to mitigating heavy metal pollution in industrial settings.

Data availability statement

Data will be made available upon a reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author used Chatgpt in order to improve the readability and language of the manuscript file. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Funding statement

A specific grant was not allocated for this study from funding or other institutions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The researcher extends heartfelt appreciation to the University of Gondar, specifically the Departments of Environmental and Occupational Health and Safety, and Chemistry and Biotechnology for their collaboration and support during the experimentation process. Additionally, sincere thanks are extended to the managers and workers of Kokeb Paint Factory for granting consent to collect necessary samples, facilitating onsite tests, and providing vital information about the factory.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2025.e42281.

References

[1] A. Priya, et al., The war using microbes: a sustainable approach for wastewater management, Environ. Pollut. 275 (2021) 116598.
[2] J. Ahmed, A. Thakur, A. Goyal, Industrial Wastewater and its Toxic Effects, 2021.
[3] N. Akhtar, et al., Various natural and anthropogenic factors responsible for water quality degradation: a review, Water 13 (19) (2021) 2660.
[4] I. Bashir, et al., Concerns and threats of contamination on aquatic ecosystems. Bioremediation and Biotechnology: Sustainable Approaches to Pollution Degradation, 2020, pp. 1–26.
[5] O.I. Ogidi, U.M. Akpan, Aquatic biodiversity loss: impacts of pollution and anthropogenic activities and strategies for conservation, in: Biodiversity in Africa: Potentials, Threats and Conservation, Springer, 2022, pp. 421–448.
[6] T. Adane, A. Dessie, Adaptability of Teff husk activated carbon for removal of hexavalent chromium from tannery wastewater at optimized process condition, Appl. Water Sci. 10 (8) (2020) 1–7.
[7] V. Linderhof, T. De Lange, S. Reinhard, The dilemmas of water quality and food security interactions in low-and middle-income countries, Frontiers in Water 3 (2021) 736760.
[8] A. Tariq, A. Mushtaq, Untreated wastewater reasons and causes: a review of most affected areas and cities, Int. J. Chem. Biochem. Sci 23 (2023) 121–143.
[9] E. Assegide, et al., A synthesis of surface water quality in Awash Basin, Ethiopia, Frontiers in water 4 (2022) 782124.
[10] M. Getachew, et al., Challenges for water quality protection in the greater metropolitan area of Addis Ababa and the upper awash basin, Ethiopia–time to take stock, Environ. Rev. 29 (1) (2021) 87–99.
[11] H. Needleman, D. Gee, *Lead in petrol makes the mind give way.* Late lessons from early warnings: science, precaution, Innovation 1 (2013) 46–79.
[12] M. El-Shazly, E. Hasanin, M. Kamel, Appropriate technology for industrial wastewater treatment of paint industry, Am.-Eurasian J. Agric. Environ. Sci. 8 (5) (2010) 597–601.
[13] V. Kumar, S. Dwivedi, S. Oh, A critical review on lead removal from industrial wastewater: recent advances and future outlook, J. Water Proc. Eng. 45 (2022) 102518.
[14] R. Harrison, Lead Pollution: Causes and Control, Springer Science & Business Media, 2012.
[15] R. Csa, The Federal Democratic Republic of Ethiopia Central Statistical Agency Report on Area and Production of Major, Statistical Bulletin, 2016.
[16] Mwai, L., J. Onyatta, and F.H. Were, Lead in Automotive Paints: A Potential Source of Exposure and Environmental Contamination. Available at: SSRN 4051266.
[17] D. Berihun, Y. Solomon, Assessment of the physicochemical and heavy metal concentration from effluents of paint industry in Addis Ababa, Ethiopia, Int. J. Wine Res. 7 (4) (2017) 1–5.
[18] B. Firdissa, Y.S.T. Soromessa, Assessment of the status of industrial waste water effluent for selected industries in Addis Ababa, Ethiopia, Assessment 6 (17) (2016) 1–15.
[19] A. Kumar, et al., Lead toxicity: health hazards, influence on food chain, and sustainable remediation approaches, Int. J. Environ. Res. Publ. Health 17 (7) (2020) 2179.
[20] R.R. Karri, G. Ravindran, M.H. Dehghani, Wastewater—sources, toxicity, and their consequences to human health, in: Soft Computing Techniques in Solid Waste and Wastewater Management, Elsevier, 2021, pp. 3–33.
[21] T.B. Woldeamanuale, A.S. Hassen, Toxicity study of heavy metals pollutants and physico-chemical characterization of effluents collected from different paint industries in Addis Ababa, Ethiopia, J. Forensic Sci. Crim. Investig 5 (2017) 555685.
[22] G. Yirdaw, A. Dessie, T.A. Birhan, Optimization of process variables to prepare activated carbon from Noug (Guizotia abyssinica cass.) stalk using response surface methodology, Heliyon 9 (6) (2023) e17254.
[23] G. Yirdaw, et al., Application of Noug (Guizotia abyssinica cass.) stalk activated carbon for the removal of lead (II) ions from aqueous solutions, Heliyon 10 (9) (2024) e30532.
[24] M.E. Awual, et al., Ligand imprinted composite adsorbent for effective Ni (II) ion monitoring and removal from contaminated water, J. Ind. Eng. Chem. 131 (2024) 585–592.
[25] M.S. Hossain, et al., Benign separation, adsorption, and recovery of rare-earth Yb (III) ions with specific ligand-based composite adsorbent, Process Saf. Environ. Protect. 185 (2024) 367–374.
[26] A.I. Rasee, et al., Efficient separation, adsorption, and recovery of Samarium (III) ions using novel ligand-based composite adsorbent, Surface. Interfac. 41 (2023) 103276.
[27] M.C. Sheikh, et al., Toxic cadmium (II) monitoring and removal from aqueous solution using ligand-based facial composite adsorbent, J. Mol. Liq. 389 (2023) 122854.
[28] R. Waliullah, et al., Optimization of toxic dye removal from contaminated water using chitosan-grafted novel nanocomposite adsorbent, J. Mol. Liq. 388 (2023) 122763.
[29] M.M. Hasan, et al., Facial conjugate adsorbent for sustainable Pb (II) ion monitoring and removal from contaminated water, Colloids Surf. A Physicochem. Eng. Asp. 673 (2023) 131794.
[30] M.R. Awual, An efficient composite material for selective lead (II) monitoring and removal from wastewater, J. Environ. Chem. Eng. 7 (3) (2019) 103087.
[31] M.S. Salman, et al., Optical detection and recovery of Yb (III) from waste sample using novel sensor ensemble nanomaterials, Microchem. J. 162 (2021) 105868.
[32] M.R. Awual, Ring size dependent crown ether based mesoporous adsorbent for high cesium adsorption from wastewater, Chem. Eng. J. 303 (2016) 539–546.

[33] M.R. Awual, et al., Introducing an amine functionalized novel conjugate material for toxic nitrite detection and adsorption from wastewater, J. Clean. Prod. 228 (2019) 778–785.
[34] J. Simon, Adsorption of Pb (Ii) from Aqueous Solution Solution onto Microwave and Conventional Method Prepared Activated Carbon from Teff Husk Using Zncl2 as an Activated Agent, 2018.
[35] G. García-Rosales, A. Colín-Cruz, Biosorption of lead by maize (Zea mays) stalk sponge, J. Environ. Manag. 91 (11) (2010) 2079–2086.
[36] M. Moyo, et al., Adsorption batch studies on the removal of Pb (II) using maize tassel based activated carbon, J. Chem. 2013 (2013).
[37] H. Amer, A. El-Gendy, S. El-Haggar, Removal of lead (II) from aqueous solutions using rice straw, Water Sci. Technol. 76 (5) (2017) 1011–1021.
[38] H.M. Hashem, M. El-Maghrabey, R. El-Shaheny, Inclusive study of peanut shells derived activated carbon as an adsorbent for removal of lead and methylene blue from water, Sci. Rep. 14 (1) (2024) 13515.
[39] A. Arul, et al., Enhanced removal of Pb (II) and Cd (II) ions from aqueous systems using coated magnetic nanoparticles in activated carbon derived from corncob waste, Surface. Interfac. 40 (2023) 103095.
[40] W. Somyanonthanakun, et al., Studies on the adsorption of Pb (II) from aqueous solutions using sugarcane bagasse-based modified activated carbon with nitric acid: kinetic, isotherm and desorption, Chemical Physics Impact 6 (2023) 100181.
[41] A. Melliti, et al., Low-cost date palm fiber activated carbon for effective and fast heavy metal adsorption from water: characterization, equilibrium, and kinetics studies, Colloids Surf. A Physicochem. Eng. Asp. 672 (2023) 131775.
[42] R. Divahar, et al., Lemon peel activated carbon: a sustainable solution for lead ion removal from E-waste bioleachate, Sustainable Chemistry for the Environment 6 (2024) 100094.
[43] O.Y. Bakather, Eco-friendly biosorbent for lead removal: activated carbon produced from grape wood, Desalination Water Treat. 317 (2024) 100210.
[44] M. Jalali, F. Aboulghazi, Sunflower stalk, an agricultural waste, as an adsorbent for the removal of lead and cadmium from aqueous solutions, J. Mater. Cycles Waste Manag. 15 (4) (2013) 548–555.
[45] G. Issabayeva, M.K. Aroua, N.M.N. Sulaiman, Removal of lead from aqueous solutions on palm shell activated carbon, Bioresour. Technol. 97 (18) (2006) 2350–2355.
[46] M. Momčilović, et al., Removal of lead (II) ions from aqueous solutions by adsorption onto pine cone activated carbon, Desalination 276 (1–3) (2011) 53–59.
[47] B.F. Manly, Statistics for Environmental Science and Management, Chapman and Hall/CRC, 2008.
[48] V.D. Adams, Water and Wastewater Examination Manual, Routledge, 2017.
[49] L. Wojnárovits, et al., Wastewater characterization: chemical oxygen demand or total organic carbon content measurement? Molecules 29 (2) (2024) 405.
[50] T.S. Tessema, A.T. Adugna, M. Kamaraj, Removal of Pb (II) from synthetic solution and paint industry wastewater using activated carbon derived from african arrowroot (Canna indica) stem, Adv. Mater. Sci. Eng. 2020 (2020) 1–10.
[51] L.D. Grant, Lead and compounds. Environmental Toxicants: Human Exposures and Their Health Effects, 2020, pp. 627–675.
[52] Y. Asrat, et al., Adsorption phenomenon of arundinaria alpina stem-based activated carbon for the removal of lead from aqueous solution, J. Chem. 2021 (2021) 1–9.
[53] S.F.S. Draman, et al., Adsorption of lead (II) ions in aqueous solution using selected agro-waste, ARPN J. Eng. Appl. Sci. 10 (1) (2015) 297–300.
[54] C.O. Thompson, A.O. Ndukwe, C.O. Asadu, Application of activated biomass waste as an adsorbent for the removal of lead (II) ion from wastewater, Emerging Contam. 6 (2020) 259–267.
[55] R.V. Raikar, S. Correa, P. Ghorpade, Removal of lead (II) from aqueous solution using natural and activated rice husk, International Research Journal of Engineering and Technology 2 (3) (2015) 1677–1685.
[56] S. Srisorrachatr, Modified sunflower seed husks for metal ions removal from wastewater, Chemical engineering transactions 57 (2017) 247–252.
[57] S. Alseekh, et al., Mass spectrometry-based metabolomics: a guide for annotation, quantification and best reporting practices, Nat. Methods 18 (7) (2021) 747–756.
[58] YB Gelaw, H Dagne, B Adane, G Yirdaw, M Moges, Z Aneley, L Kumlachew, A Aschale, YA Deml, E Tegegne, TA Birhan, Adsorptive removal of cadmium (II) from wastewater using activated carbon synthesized from stem of Khat (Catha edulis), Heliyon 10 (22) (2024 Nov 30).
[59] M.S. Ismail, et al., Facile preparation of amine-functionalized corn husk derived activated carbon for effective removal of selected heavy metals from battery recycling wastewater, Heliyon 8 (5) (2022) e09516.
[60] A.A. Adetokun, S. Uba, Z.N. Garba, Optimization of adsorption of metal ions from a ternary aqueous solution with activated carbon from Acacia Senegal (L.) Willd pods using Central Composite Design, J. King Saud Univ. Sci. 31 (4) (2019) 1452–1462.
[61] M. Kavand, P. Eslami, L. Razeh, The adsorption of cadmium and lead ions from the synthesis wastewater with the activated carbon: Optimization of the single and binary systems, J. Water Proc. Eng. 34 (2020) 101151.
[62] A. Azizullah, et al., Heavy metals pollution in surface waters of Pakistan, Anthropogenic Pollution of Aquatic Ecosystems (2021) 271–312.
[63] L. Bouida, et al., A review on cadmium and lead contamination: sources, fate, mechanism, health effects and remediation methods, Water 14 (21) (2022) 3432.
[64] S. Kumbhakar, et al., Lead induced-toxicity in vegetables, its mitigation strategies, and potential health risk assessment: a review, Int. J. Environ. Sci. Technol. 20 (5) (2023) 5773–5798.