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Research article

Utilization of industrial solid wastes as filter media for efficient dye removal in wastewater treatment

Balaji Ravi, Deepasree Srinivasan, Arun Murugesan, Karthick Jaisankar *

Department of Civil Engineering, PSG Institute of Technology and Applied Research, Neelambur, Coimbatore, Tamil Nadu 641062, India

A R T I C L E I N F O

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A B S T R A C T

The continuous discharge of wastewater from various industries significantly pollutes the environment and disrupts ecological balance. Simultaneously, vast quantities of industrial solid waste such as waste foundry sand (WFS), red mud (RM), and quarry waste (QW) are frequently disposed of in landfills. This study explores the utilization of industrial solid wastes (WFS, RM, and QW) as alternative sand filter media in sand filtration for the treatment of industrial dye effluents. The efficiency of these materials as filter media was evaluated both individually and in equal-proportion combinations, with performance compared against conventional river sand filters. The characteristics of the treated effluent were analysed its physicochemical properties and its dye adsorption efficiency assessed using UV–visible spectroscopy. The combination of WFS, RM, and QW as filter media demonstrated significant dye removal efficiency, with WFS showing the highest performance, followed by RM and QW, achieving an overall dye removal efficiency of up to 95.98 %. The findings of this study provide valuable insights into sustainable waste resource utilization, offering a promising approach for improving wastewater treatment efficiency.

1. Introduction

The various industrial processes generate significant amounts of solid waste, including fly ash from coal combustion, waste foundry sand (WFS) from ferrous and non-ferrous industries, ground granulated blast furnace slag from steel production, red mud (RM) from aluminum industry, and quarry waste (QW) from granite quarries. These wastes pose serious ecological concerns due to their low utilization rates relative to their high production volumes [1,2]. Although they have been repurposed in applications such as supplementary cementitious materials, fillers, soil amendments, road construction, landfill liners, retaining structures, and barrier systems accounting for approximately 20–30 % utilization in recent studies, there remains a significant gap between waste generation and effective reuse. Addressing this gap requires innovative, environmentally friendly technologies. [3–10].

Ensuring environmental compliance in managing industrial effluent discharge has become increasingly challenging due to rapid industrialization, which has significantly escalated water consumption demands [11]. Industrial effluents from sectors such as textiles, paper, plastics, leather, pharmaceuticals, and cosmetics contain high levels of impurities, suspended solids, and dye contaminants [12]. These pollutants have severe environmental consequences, including heavy metal leaching, soil and groundwater contamination [13,14]. Various treatment methods are employed to mitigate industrial wastewater pollution, including physical processes such as sand filtration, nanofiltration, ultrafiltration, and activated carbon adsorption, as well as chemical methods like coagulation, flocculation, ozonation, photocatalysis, ultraviolet disinfection, and advanced oxidation processes [15–17]. Among these, sand filtration and activated carbon adsorption are the most widely used due to their efficiency. However, these technologies often pose economic challenges due to high operational and material production costs [18–21].

Silicon dioxide (SiO_2)-enriched sand is commonly used as a filter medium in sand filtration for the removal of suspended solids. Typically, river sand with an SiO_2 content exceeding 85 % is utilized for filtration. In activated carbon adsorption, carbon serves as an excellent adsorbent for removing dye molecules from industrial effluents. Commercially available activated carbon, along with synthesized forms such as carbon nanotubes, graphene, coal-derived biochar, and other carbonaceous materials produced at elevated temperatures from 600 °F to 1200 °F,

* Corresponding author.
E-mail addresses: balaji.civil@psgitech.ac.in (B. Ravi), deepasree@psgitech.ac.in (D. Srinivasan), arun@psgitech.ac.in (A. Murugesan), karthickjaisankar16@gmail.com (K. Jaisankar).

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Table 1
Surface characterization of solid wastes.

Parameter	Surface area (m^2/g)	Pore volume (cc/g)	Pore diameter dv (d)
WFS	6.311	0.020	2.448
RM	10.960	0.044	1.427
QW	14.106	0.076	1.432

have been utilised for adsorption. However, the long-term sustainability and availability of these resources remain uncertain.

On comparing the filtration process with other techniques like membrane filtration using electrospinning, fabrication, carbon-based adsorbent, the filtration approach is simple and convenient. For example, in case of membrane filtration fabricated using Electrospinning technique, requires a lot of energy and power during the membrane fabrication process. This works under very high voltage during the membrane fabrication. Likewise, carbon-based adsorbent in treatment of wastewater, the synthesis of carbon forms also utilises plenty of energy through pyro-process. Whereas, the dumped solid wastes from different industry doesn't require additional energy for the treatment process. As this material can be utilised and replaced directly in conventional sand filtration. In this study, industrial solid wastes with high SiO_2 content namely, WFS (89 %), RM (66 %), and QW (67 %) are investigated as alternative filter media for sand filtration. Beyond their silica content, the presence of carbon in WFS, iron oxide (Fe_2O_3) in RM, and metal oxides in QW could be the potential cause for dye adsorption and degradation. This approach offers a dual benefit such as effective dye decolorization aas well as suspended solids removal [11,12,22,23,24].

To bridge this research gap, the present study investigates the efficiency of untreated industrial solid waste in wastewater treatment, both individually and in combination. Here, the solid waste materials are characterized based on surface area and particle size distribution for assessing its filtration and adsorption characteristics. The samples from raw and treated wastewater samples are analysed for physicochemical properties, heavy metal leachate characteristics, and dye adsorption by UV–visible spectroscopy. In addition to that, Langmuir and Freundlich isotherms models are utilised to assess the adsorption behaviour of the industry waste materials. This study aims to determine the effectiveness of industrial solid waste as an alternative, sustainable filter medium for industrial dye effluent treatment.

2. Materials and methods

2.1. Materials

The filter bed media, namely WFS, RM, and QW were sourced from PSG Foundry in Coimbatore, a local market in Salem, and a quarry industry in Coimbatore, respectively. Likewise, the industrial effluent was collected from a textile industry in Tirupur, India.

2.2. Material characterization

Industrial solid wastes are characterized using Brunauer-Emmett-Teller surface analyzer, Fourier Transform Infrared (FTIR) spectroscopy and Energy Dispersive X-ray (EDX) spectroscopy. From the BET analysis, surface area, isotherm analysis, and pore size distribution of the solid wastes (WFS, RM, and QW) within the mesoporous range were determined and are presented in Table 1 and Fig. 1. The industrial solid wastes exhibited a high surface area ranging from 6 to 15 m^2/g and a pore volume of 0.01–0.08 cc/g. Among these materials, WFS exhibited the highest surface area, followed by RM and QW.

The particle size distribution of the solid wastes is illustrated in Fig. 2a. The presence of silica (SiO_2) in the industrial solid wastes was confirmed through FTIR spectral analysis using the attenuated total

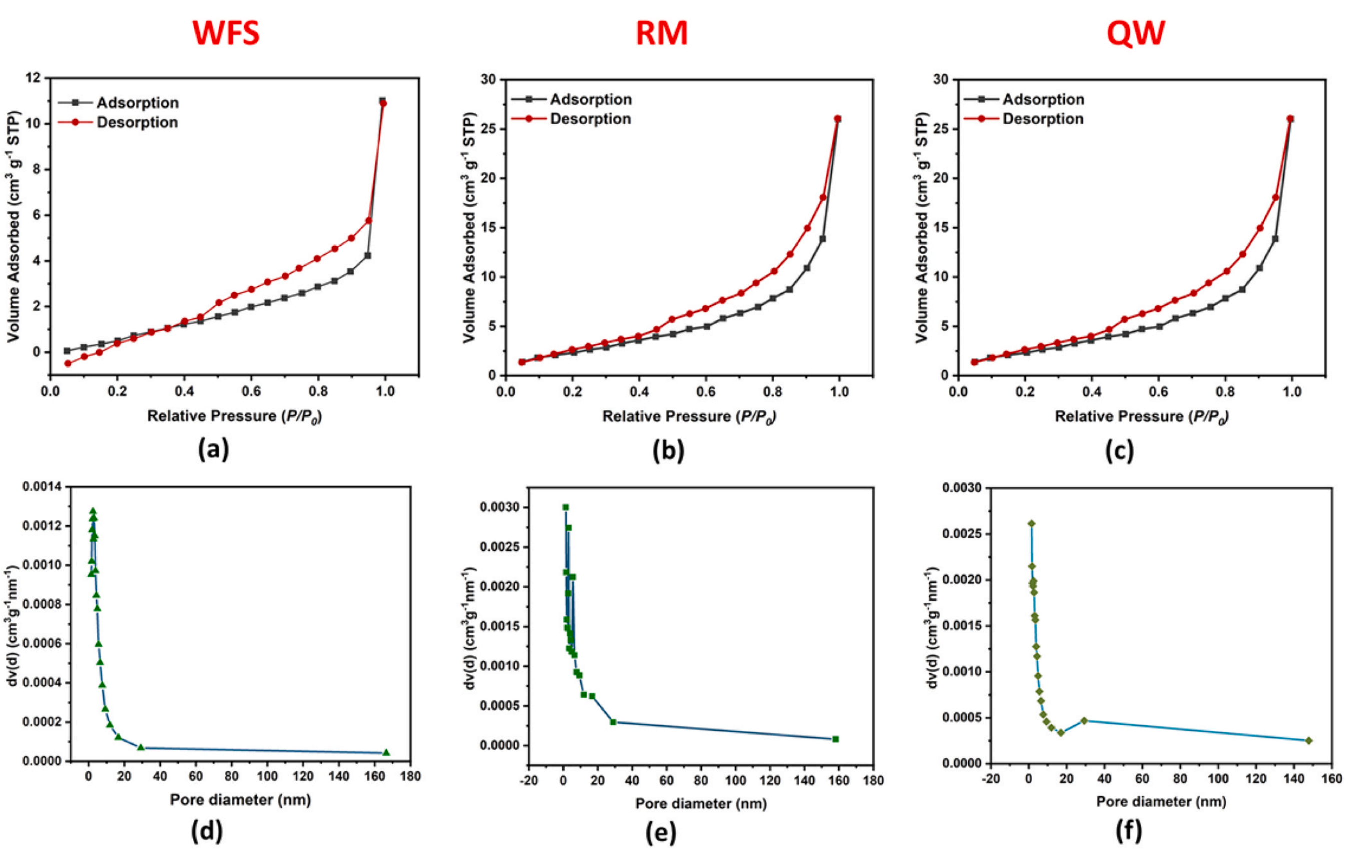

Fig. 1. Isotherm (a-c) and pore diameter (d-f) of solid wastes.

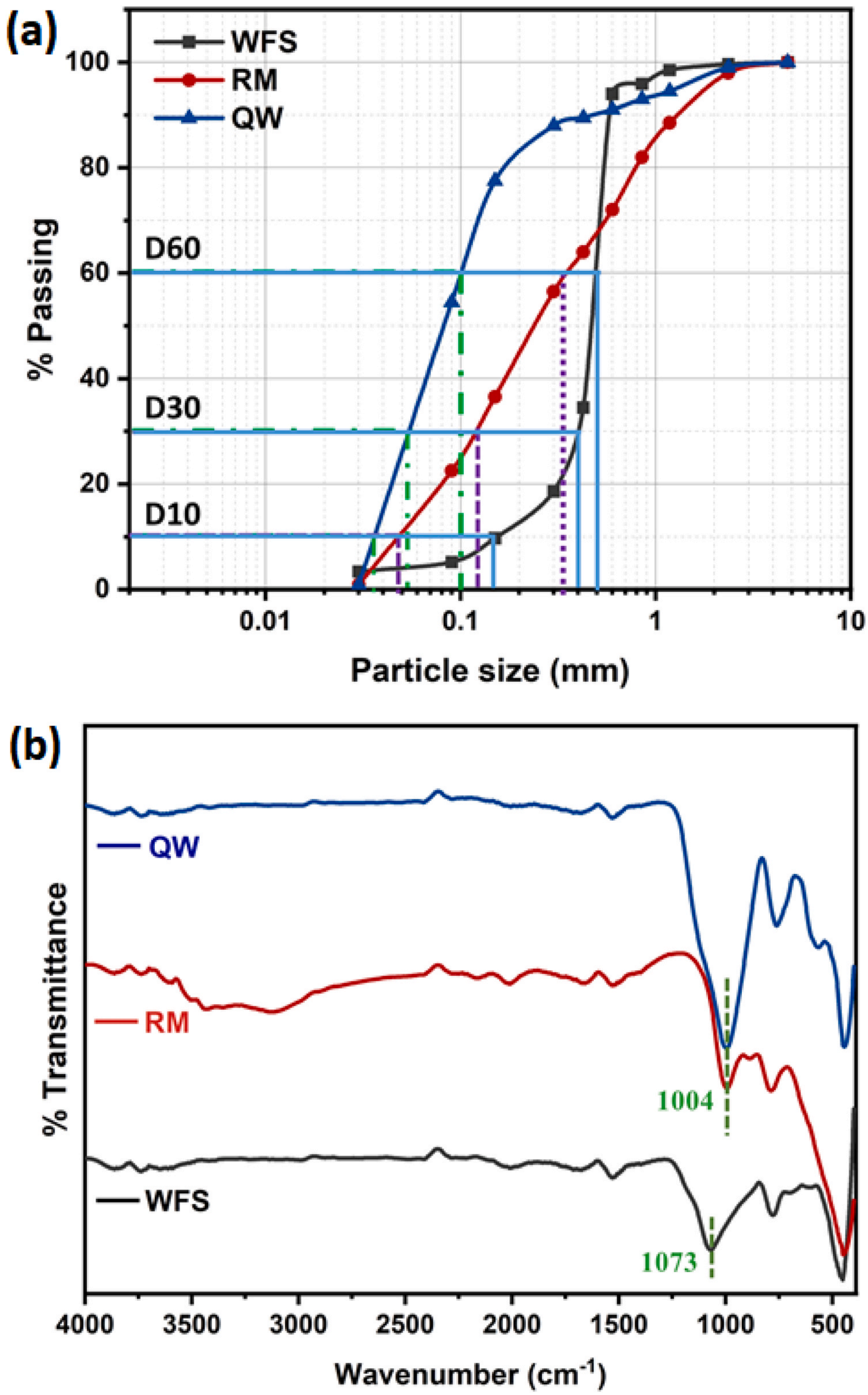

Fig. 2. (a) Particle size distribution, (b) FTIR spectrum of solid wastes.

reflection (ATR) method with a Shimadzu IR Affinity-IS instrument. The characteristic silica absorption band was observed at a wavenumber of 1004 cm^{-1} for QW and RM, while WFS displayed a peak at 1073 cm^{-1} (Fig. 2b). Elemental composition analysis of the solid wastes was conducted using EDX analysis which identifies the surface composition, and the results are presented in Table 2. Based on the EDX analysis, all the solid wastes contain around 30 % of carbon-based material, followed by oxygen and silicon. This demonstrates that the predominant materials are carbon and silicon dioxide.

2.3. Experimental set-up and methodology

A packed column filtration system with dimensions of 3.2 cm in diameter and 15 cm in height was fabricated to operate under applied

Table 2
Elemental composition of the solid wastes.

Elements	C	O	Na	Mg	Al	Si	Ca	Fe	Ti
	Atomic weight in percentage								
WFS	36.91	43.23	0.25	0.02	1.83	13.38	0.20	4.02	0.15
RM	29.74	45.94	1.04	0.03	2.49	6.79	0.06	13.86	0.05
QW	36.46	41.90	1.42	0.24	4.14	14.20	0.53	1.04	0.07

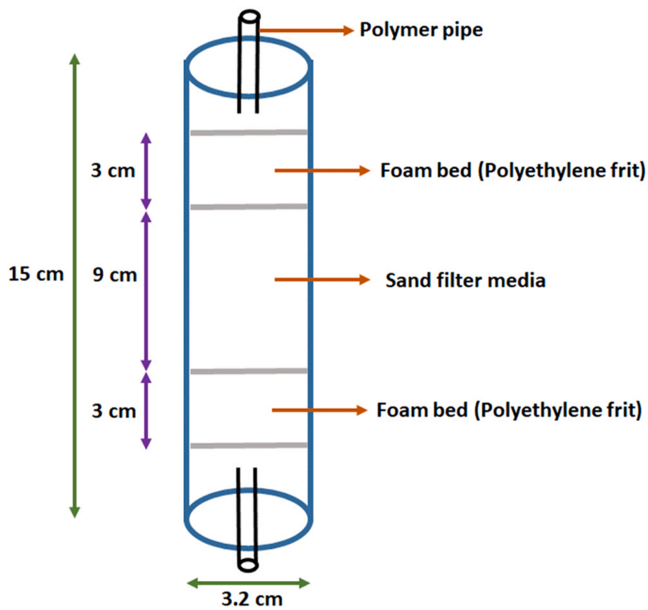

Fig. 3. Schematic representation of packed column for filtration under applied pressure.

Table 3
Physical properties of filter media.

Parameters	WFS	RM	QW	Permissible limit/WHO
pH	8.42	8.3	7.62	6.5 – 8.5
Turbidity (NTU)	0.1	0.4	5.3	< 10
Hardness (mg/L)	375	260	189	< 500
TDS × 10^3 (mg/L)	10.520	8.330	7.154	< 2000
Temperature (°C)	34	34	34	-
Yield (%)	67.48	49.96	40.07	-

pressure. The schematic representation of the setup is shown in Fig. 3. The setup was constructed using opaque plexiglass, with polymer pipes connected at both the top and bottom. A constant applied pressure of 10 kg/cm^2 was maintained throughout the treatment process. The packed column consisted of three layers: a 3 cm polyethylene frit (foam bed) at both the top and bottom, and a 9 cm sand media layer in the middle, serving as the primary filtration medium. A packed column bed consists of the sand filter media of height 9 cm. The industrial solid wastes such as WFS, RM and QW are replaced instead of the sand filter media. These systems are named as T2, T3 and T4. Dye effluents are pumped into the top of the packed bed using a peristaltic pump, passing through the filter media and the treated effluents collected at the bottom end, whereas the industrial solid wastes act as a filter media. Treated effluent samples from each industrial waste are assessed for its physiochemical properties. In case of T5 and T6, combinations of each filter media with a height of 3 cm were loaded in the filter media.

Before the sand filtration process, the industrial solid waste was thoroughly washed with hot water to remove impurities and then dried in an oven at 105°C to remove moisture content. Since the presence of oxides and heavy metals in the solid waste could potentially coagulate with water, distilled water was used to assess the physical properties of the solid waste. The water was then passed through the filter media setup containing WFS, RM, and QW, and the results are presented in Table 3. Based on the results from the physical properties, the obtained values are compared with the permissible limit provided by WHO guidelines for treated effluent for its reuse in irrigation and other uses (Table 3).

The effluent was treated using different sand media, including river sand (T1), waste foundry sand (WFS) (T2), red mud (RM) (T3), and quarry waste (QW) (T4), each used at 100 % concentration. Additionally, T5 and T6 represent the combined effect of solid waste mixtures, specifically WFS:RM:QW and QW:RM:WFS, respectively, in a 1:1:1 ratio. The packing order of solid waste in T5 and T6 was determined based on dye decolorization efficiency and particle size distribution. The characteristics of the treated effluent from T1 to T6 were then compared with the raw textile effluent (TE) to evaluate treatment performance.

2.4. Characterization

The physical properties of the sample were assessed, including its pH (measured using a pH meter), turbidity (measured using a nephelometer), hardness (measured by the Versanate method with the Eriochrome Black T indicator), and the presence of organic and inorganic substances (determined by Total Dissolved Solids, TDS). The leachate of heavy metals from the solid waste during filtration was analyzed using the ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy). The treated wastewater was diluted with distilled water to achieve the working concentration for ICP-OES analysis. The adsorption kinetics of the treated sample were measured by UV-Vis absorbance at wavelengths ranging from 200 to 800 nm using a Hitachi UH5700 UV-Vis-NIR spectrophotometer. Desorption activities of the solid waste, including degradation or adsorption, were assessed by taking 0.5 g of effluent-filtered solid waste and adding 10 mL of ethanol. The mixture was allowed to rest for 3 hours, and any changes in dye color indicated the desorption of the solid waste. For filtration studies and model prediction, 50 mL of dye effluent was used, with 40 g of solid waste serving as the filter medium throughout the experiment. The Langmuir model, which assumes monolayer adsorption of dye molecules, was applied, while the Freundlich model, which accounts for multilayer adsorption on the filter bed surface, was also considered.

3. Results and discussion

3.1. Physiochemical properties

The pH of both the effluent and the treated samples using solid waste was determined and is presented in Fig. 4a. The textile effluent (TE) had a pH of 6.26, which falls within the permissible range of 5–8.5. In contrast, all treated samples (T1–T6) filtered through sand media exhibited neutral pH values, ranging from 7.46 to 7.92. These values indicate that the sand media effectively neutralized the effluent. The observed increase in pH is attributed to the presence of metal oxides in the sand media, as well as its composition. Among the industrial solid wastes, the pH trend was found to be WFS > RM > QW, with WFS containing the highest percentage of metal oxides, particularly magnesium oxide and calcium carbonate, compared to RM and QW. Additionally, the pH values of the treated samples using industrial solid waste

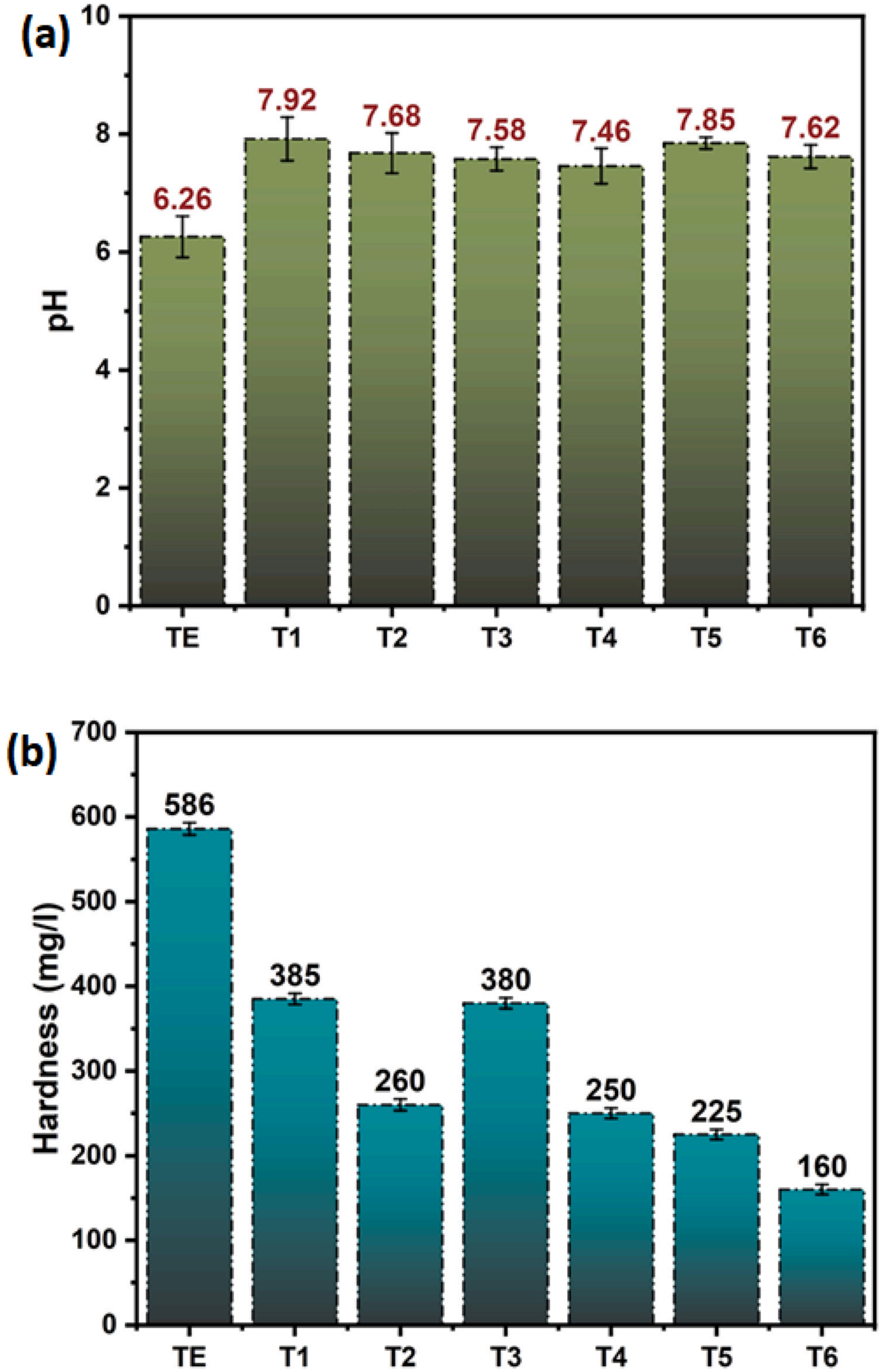

Fig. 4. (a) pH of effluent and treated samples, (b) Hardness of effluent and treated samples.

remained within the permissible limit.

The hardness of water, classified as either permanent or temporary, is determined by the concentration of magnesium and calcium salts. The textile effluent (TE) had a high hardness of 586 mg/L, indicating the presence of both permanent and temporary hardness. After treatment through sand filtration, the hardness of the treated samples (T1–T6) ranged from 150 to 390 mg/L, demonstrating an efficient removal of hardness by 30–75 %, as shown in Fig. 4b.

Turbidity of water indicates the concentration of suspended impurities present. The turbidity of the textile effluent (TE) was measured at 4.3 NTU. In contrast, after sand filtration (T1–T6), the turbidity of the treated effluent decreased by 36–70 %, as shown in Fig. 5a. This reduction in turbidity is attributed to the high surface area of the solid waste, which prevents solid particles from drifting over the filter media, effectively removing colloidal and suspended impurities from the effluent.

The Total Dissolved Solids (TDS) concentration of the sample is a key indicator of its suitability for various applications, such as drinking,

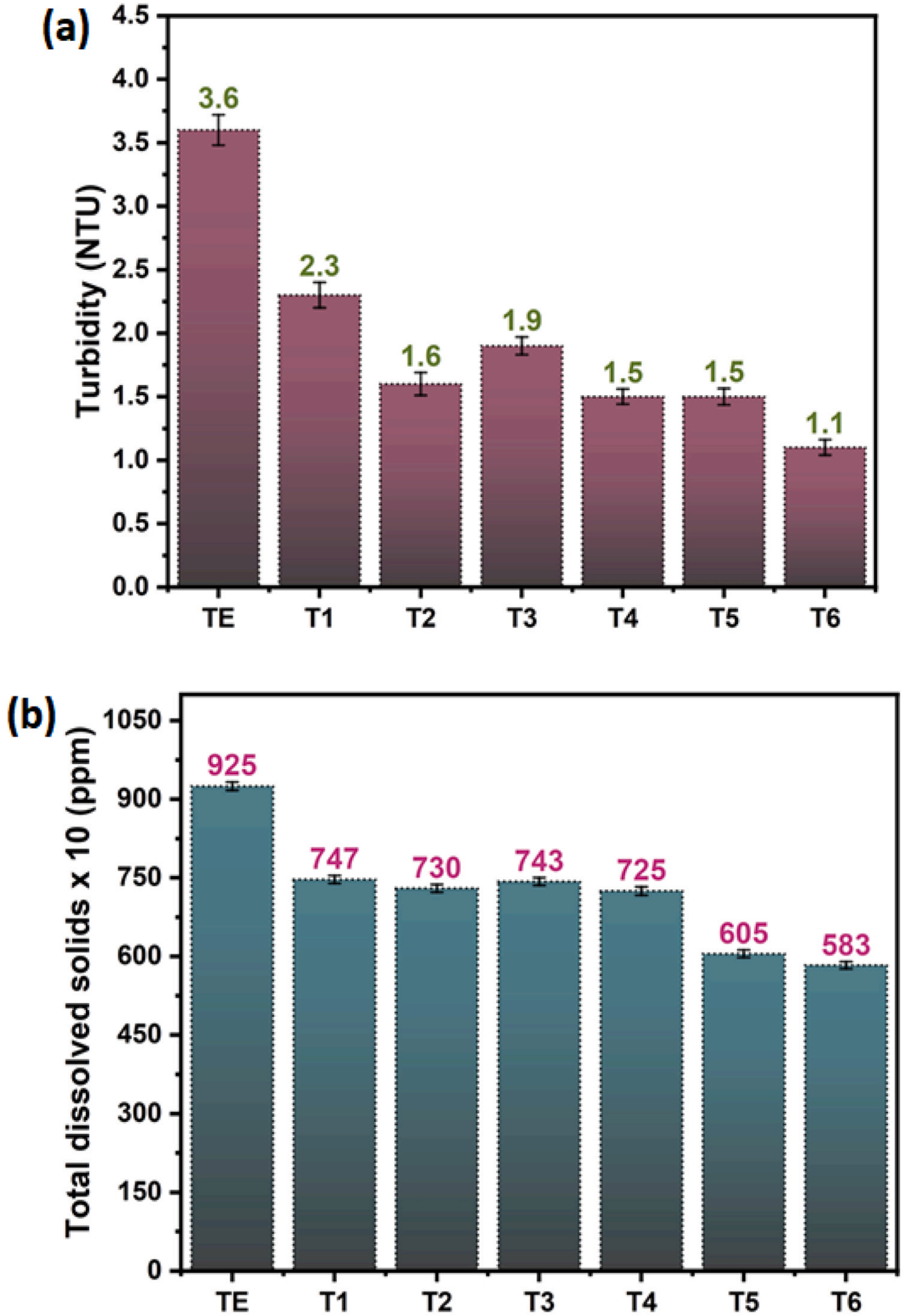

Fig. 5. A Turbidity of effluent and treated samples. b TDS of effluent and treated samples.

industrial use, or irrigation. A similar trend was observed in the TDS levels of the textile effluent (TE) and the treated samples (T1–T6), as depicted in Fig. 5b. A linear correlation between turbidity and TDS is shown in Fig. 6. According to the World Health Organization (WHO) and Indian Standards Institute (ISI), the allowable limit for dissolved solids in drinking water is 1500 mg/L. Therefore, although the treated samples do not meet the standards for drinking water, they are suitable for alternative applications such as irrigation and gardening. The yield of treated effluent for each sample was as follows: T1 = 82.30 %, T2 = 64.48 %, T3 = 54.7 %, T4 = 46.9 %, T5 = 36.15 %, and T6 = 35.46 %.

3.2. *Leachate*

During the filtration process, heavy metals and metal oxides present in the solid waste may leach into the effluent. As a result, the concentration of metals in the treated water was recorded (Table 4). It was observed that the treated effluent from different sand media exhibited similar concentrations of Co, Ni, Cr, Cu, As, and Pb, except for Al. Both the textile effluent (TE) and the treated effluent (T1–T6) showed no detectable concentration of Co and Ni, with concentrations of 0.01 ppm for Cr and Cu, and 0.03–0.05 ppm for As and Pb. Among these elements, Al exhibited significantly higher concentrations, ranging from 0.06 to 0.14 ppm. Notably, the treated effluent using WFS and RM as filter

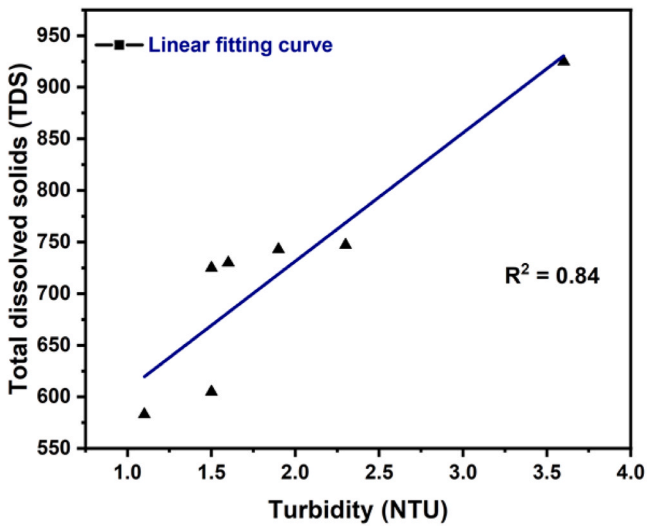

Fig. 6. Correlation curve between Turbidity and TDS.

media showed about double the concentration of Al compared to the TE. This increased concentration of Al in the WFS and RM treated effluent could be attributed to the source of WFS and RM, which are derived from aluminum industries. However, these concentrations remain below the permissible limits according to the World Health Organization (WHO).

3.3. Dye adsorption efficiency

The treated effluent filtered through various sand media (T1–T6) was analyzed using UV-Visible spectroscopy. The absorption spectrum of the treated effluent provides clear insight into dye adsorption, as shown in Fig. 7a. Although the specific type of dye used in the industry is unknown due to industrial confidentiality, the absorption spectrum allows for the identification of the dye based on its characteristic peak. The textile effluent (TE) exhibits intense peaks at approximately 612 and 662 nm, which correspond to the absorption range of methylene blue dye, as the intense peak for this dye typically lies between 600 and 665 nm. The treated effluent samples (T1–T6) show progressively reduced intensity, following the order: T5 > T2 > T6 > T3 > T4 > T1 > TE. The dye removal efficiency of the treated samples was calculated using Eq. 1, and the results are presented in Table 5.

$$\text{Dye removal efficiency}(\%) = \frac{Q_i - Q_e}{Q_i} \times 100 \tag{1}$$

Where, Q_i – dye adsorption of raw effluent (TE)

Q_e – dye adsorption of treated effluent (T1-T6)

Further analysis of the absorption spectra (Fig. 7) reveals that the treated effluent samples (T5, T2, T6) show the complete disappearance of absorption peaks between 612 and 662 nm, indicating that most of the dye has either been degraded or adsorbed. To further characterize the solid waste in terms of adsorption or degradation, desorption studies were conducted on the filtered solid waste using ethanol. Visual observations (Fig. 7b) suggest that the solid wastes WFS, RM, and QW exhibit different behaviours: WFS shows evidence of dye degradation, RM demonstrates complete adsorption, and QW shows partial adsorption.

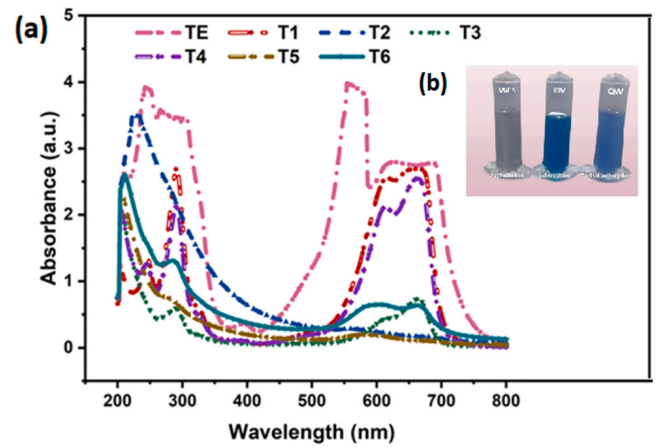

Fig. 7. (a) Dye adsorption (b) Desorption of the sample.

Table 5
Dye removal efficiency of treated effluent.

Treated effluent	Q_i	Q_e	Removal efficiency (%)
T1	2.74	2.68	2.18
T2	2.74	0.16	94.16
T3	2.74	0.73	73.33
T4	2.74	2.54	7.29
T5	2.74	0.11	95.98
T6	2.74	0.63	77.00

3.4. Isotherms

Langmuir and Freundlich isotherms models were interpreted at room temperature for effluent dye of varying concentrations 25 ppm, 50 ppm, 200 ppm and 400 ppm prepared from the dried effluent dye powder obtained from the industry. In order to analyze the nature of adsorption as well as interaction between the dye particles and filter medium (T5), both the models were analyzed. Langmuir model involves the monolayer interaction of dye whereas the Freundlich model encompasses the multilayer adsorption of dye molecules on the filter bed surface [25]. The following equations represent the Langmuir and Freundlich isotherm models and are given below,

Langmuir isotherm model:

$$\frac{C_e}{q_e} = \frac{C_e}{q_{\max}} + \frac{1}{q_{\max} b} \tag{2}$$

Freundlich isotherm model:

$$\ln qe = \ln KF + \frac{1}{n} \ln C_e \tag{3}$$

Table 4
Leachate concentration.

Elements	TE	T1	T2	T3	T4	T5	T6	Permissible limit (WHO standard)
Aluminum (Al)	0.06	0.04	0.14	0.12	0.08	0.13	0.13	0.20
Arsenic (As)	0.03	0.03	0.05	0.04	0.03	0.05	0.04	0.05
Cobalt (Co)	0	0	0	0	0	0	0	0.01
Chromium (Cr)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05
Copper (Cu)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	1.50
Nickel (Ni)	0	0	0	0	0	0	0	0.10
Lead (Pb)	0.03	0.03	0.04	0.04	0.03	0.04	0.04	0.05

Table 6
Isotherm model for adsorption of dye effluent using filtration set-up.

Filter medium	Langmuir model			Freundlich model		
	q_{max} (mg/g)	b (L mg^{-1})	R^2	K_F (mg/g (L $mg^{-1})^{1/n}$)	N	R^2
T5	85.47	0.625	0.9964	33.28	16.92	0.2446

where, C_e – Equilibrium dye concentration (mg/L)
q_e – equilibrium adsorption capacity (mg/g)
q_{max} – maximum monolayer adsorption (mg/g)
b – Langmuir constant (L/mg)
K_F – Freundlich constant (mg/g (L $mg^{-1})^{1/n}$)
n – Intensity of adsorption

Here, the R^2 value of Langmuir model corresponds to 0.9964 and for Freundlich model corresponds to 0.2446. The calculated values of both the isotherm models are presented in Table 6 and Fig. 8. Based on the R^2 value, the adsorption in the filter medium is monolayer adsorption and the maximum adsorption capacity was 85.47 mg/g follows the Langmuir model. On increasing the concentration of dye effluent, the removal efficiency value decreases after certain limit. This is due to fact that the monolayer adsorption favors the dye removal, on increasing the concentration above the adsorption capacity, removal efficiency starts declining. From the R^2 value of Freundlich model, dye removal is not favoured for the multilayer adsorption.

3.5. Nut shell discussion

Based on the findings, it can be inferred that industrial solid waste rich in SiO_2 is highly effective in sand filtration, providing efficient treatment of the effluent. The physico-chemical properties of the treated effluent using industrial solid waste are nearly identical to those of river sand. In addition to the chemical composition of SiO_2, the particle size of WFS, RM, and QW also plays a significant role in the treatment process. The elemental composition of carbon in the solid waste, ranging from 29 % to 39 %, contributes effectively to the decolorization of dyes. WFS exhibits dye degradation properties, while RM and QW are more effective in dye adsorption. Therefore, industrial solid waste rich in SiO_2 offers a promising alternative to conventional sand media (river sand), with dual benefits of effluent treatment and dye decolorization.

When compared to traditional wastewater treatment methods, the proposed use of SiO_2-rich industrial waste solids, such as waste foundry sand (WFS), red mud (RM), and quarry waste (QW), for dye removal offers several advantages. These waste materials provide a cost-effective and environmentally friendly substitute for chemical treatments like flocculation and coagulation, which need costly reagents and produce secondary sludge. Even though activated carbon has long been used for dye adsorption, it is expensive and difficult to regenerate, but industrial waste is abundant and inexpensive. In addition to eliminating colors and improving effluent quality, the solid wastes have a high filtering efficiency that is comparable to sand filtration. Although complex dyes can be effectively broken down by advanced oxidation processes (AOPs), these processes require large energy inputs and greater operating costs; for this reason, the industrial waste technique is more scalable and energy efficient. Recycling the items reduces resource use and landfill waste, which promotes a circular economy. However, additional research should be done on some hazards including metal leaching and performance differences with other colors.

These treated effluents can be safely discharged into the environment without posing risks to the ecosystem and can be recommended for domestic use, gardening, and industrial reuse. A limitation of this study is the secondary treatment of solid waste by hot water washing, though this treatment process has shown promising effects on the final treated sample. The valorization of solid waste in environmental engineering contributes to achieving sustainable development goals, particularly SDG 6 (Clean Water and Sanitation) and SDG 9 (Industry, Innovation, and Infrastructure).

The study demonstrates that SiO_2-rich industrial solid waste, when incorporated into sand media, significantly improves wastewater treatment by reducing turbidity, hardness, TDS, and removing dye contaminants effectively, as evidenced by UV-Visible spectroscopy results. This innovative approach provides a sustainable solution by repurposing industrial solid waste for tertiary effluent treatment, eliminating the need for landfill disposal while aligning with environmentally friendly practices.

4. Conclusion

The present study explores the utilization of SiO_2-rich industrial solid waste in sand filtration for wastewater treatment. The treated effluent demonstrated significant improvements in its physical properties, with turbidity reduced by 70 %, hardness reduced by 75 %, and TDS reduced by 37 % compared to the untreated textile effluent. Moreover, the dye removal efficiency for T5 filter media is 95.98 %, whereas the filter media T2 has a removal efficiency of 94.16 % stand next to it. Thus, in the tertiary treatment of effluent, SiO_2-rich solid waste with encapsulated carbon in the sand media effectively treated and decolorized the effluent. Therefore, rather than being disposed of in landfills, this solid waste can be effectively repurposed, offering a sustainable solution aligned with its inherent properties.

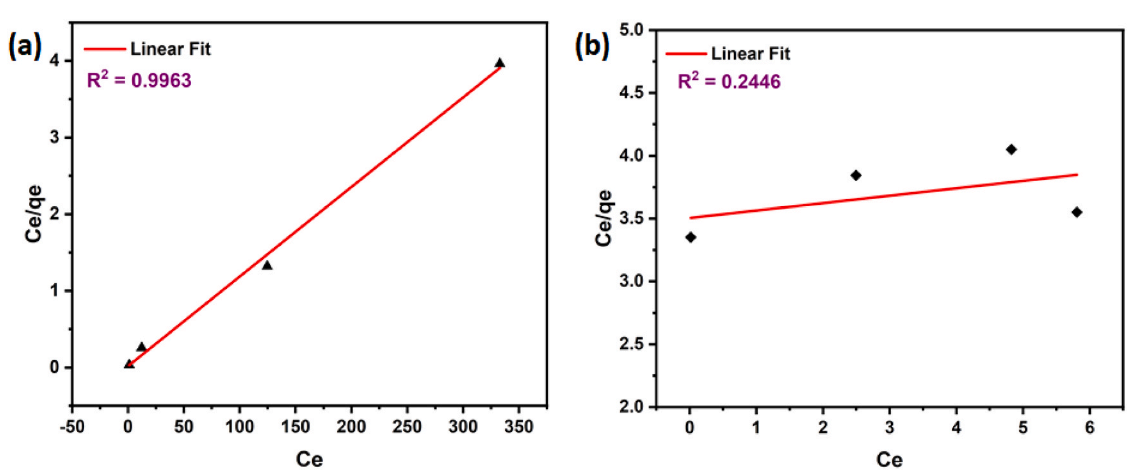

Fig. 8. (a) Langmuir model (b) Freundlich model.

Ethics approval and consent to participate

Not applicable.

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

During the preparation of this work the author(s) used Chat GPT in the writing process in order to improve the readability and language of the manuscript. 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 published article.

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.

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Consent for publication

Not applicable.

Data availability

Data will be made available on request.

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