Comparative Study of Commercial and Plastic Waste Resins for Groundwater Treatment

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Article Info

Abstract

Groundwater contamination by organic and inorganic pollutants poses serious health and environmental concerns. Conventional resins are effective but costly. There is a need for low-cost, eco-friendly alternatives, particularly through plastic waste valorization. This study compares the performance of commercial and plastic waste resins for groundwater treatment. Scanning electron microscopy analysis revealed that the commercial resin had a smooth, porous structure, while the plastic waste resin showed a rough, irregular surface. Energy dispersive X-ray and Fourier transform infrared spectroscopy analysis confirmed key ion exchange functional groups, including sulfonic acid, in the commercial resin. X-ray diffraction analysis showed the commercial resin was amorphous with low crystallinity. Results showed that the commercial resin outperformed the plastic waste resin by removing 98.6% biochemical oxygen demand (BOD), 85% chemical oxygen demand (COD), 88.9% total suspended solids (TSS), 50% total dissolved solids (TDS), and 66% iron. The plastic waste resin achieved lower removal rates of 66.7% TSS, 25% TDS, and 19.2% COD. In column method, the commercial resin removed 91.65% total hardness within 4 hours at 2163 cm^3 dosage, while the plastic waste resin achieved up to 52.12%. The superior performance is linked to the commercial resin's favorable structure and functional groups for ion exchange. The use of plastic waste resin as a potential ion exchange material for water treatment supports waste valorization and aligns with circular economy principles. However, its performance requires further optimization, which can be pursued through strategic collaboration with water treatment industries.

1. Introduction

Water plays a vital role that serves fundamental pillar of economic globalization [1]. About 2.5 billion people around the world use groundwater resources to meet basic needs. 60% of the world's groundwater is used for agriculture and homes [2]. In Malaysia, only 3% of water is extracted from groundwater sources, as surface water is the primary water supply [3]. The availability and usefulness of groundwater resources are directly linked to the abundance of accessible freshwater [4]. Nevertheless, groundwater faces numerous challenges to its quality, both from natural sources and human activities, which can limit its suitability for consumption and require intervention to ensure safety [5]. The quality of groundwater worldwide has been significantly impacted by human activities such as deforestation, industrial effluent discharge, sewage deposition, aquaculture, and mining [6]. Apart from that, natural processes such as leaching from the soil, evapotranspiration, rock weathering, and the activities of aquatic species also contribute to changes in groundwater quality [7]. These factors have led to an increase in contaminants in groundwater, deterioration of groundwater quality, harm to aquatic life, and ultimately, negative effects on human health [8].

One of the most important groundwater quality parameters is hardness. When water is hard, it requires a significant amount of soap to produce lather. Water hardness is primarily caused by the presence of calcium and magnesium ions in water [9]. Groundwater with high concentrations of calcium and magnesium leads to hard water, which can leave a crusty buildup in pipes and appliances [10]. In addition, groundwater usually has a high iron content that can make red stains on pipes and clothes. The main issue faced by industrial plants due to water hardness is the buildup of mineral scale in pipes and boilers, leading to reduced efficiency and increased energy consumption. Hence, water treatment processes are needed to remove these ions [11]. There are many processes available for groundwater treatment, including aeration, coagulation, flocculation, filtration, ozone, and ion exchange [12].

Ion exchange, in particular, is widely used and considered one of the most effective methods that can remove a wide range of contaminants, including heavy metals, radionuclides, and certain organic compounds [13]. It is commonly used to remove total hardness in groundwater, which involves using a resin to exchange calcium and magnesium ions for other ions [14]. Unlike filtration or chemical treatment, ion exchange does not produce harmful by-products and does not require the use of potentially hazardous chemicals. In addition, ion exchange systems can be easily tailored to specific contaminants, making them an extremely efficient and cost-effective solution for groundwater remediation [15]. Ion exchange and polymer resins have been successfully used to recover heavy metals from waste and industrial streams [15], [16]. Ion exchange resins have attracted a lot of attention as a material that is important for water treatment and can meet the guidelines for water quality standards [17]. Ion exchange resin can remove dissolved ions from groundwater and replace them with harmless ions through cation and anion exchange processes. The process is simple, low-cost, and environmentally friendly. Despite their effectiveness, conventional ion exchange resins face several limitations that hinder their widespread and sustainable use. These resins, typically made from synthetic polymers such as polystyrene-divinylbenzene, that can be relatively expensive to produce and regenerate, especially for large-scale applications. Over time, their performance degrades, requiring frequent replacement, which contributes to increased operational costs. Furthermore, the disposal of spent resins poses environmental challenges, as they are non-biodegradable and may retain hazardous substances that complicate safe handling and landfill management [18].

In recent years, growing concern has emerged over the increasing amount of resin-based plastic waste generated by the electronics industry [19]. Plastics have become integral to the design and manufacturing of electronic devices due to their lightweight nature, versatility, and cost-effectiveness. Compared to traditional materials such as metals, glass, and silicon, plastics significantly reduce the overall weight of electronic products. This reduction in weight not only improves portability and energy efficiency during use but also leads to lower transportation costs and reduced carbon emissions during shipping. As a result, the strategic use of plastics has enabled the electronics sector to enhance product performance while simultaneously minimizing environmental and logistical burdens [20]. An alternative way to reduce the disposal of resin plastic waste is by using it as an ion exchange resin for groundwater treatment [21]. The lack of systematic studies highlights a significant research gap in evaluating the feasibility and effectiveness of using resin plastic waste as functional ion exchange materials. Hence, this study aims to investigate the performance of resin made from plastic waste in comparison to the commercial resin for groundwater treatment.

2. Materials and Methods

2.1 Groundwater Sampling

The groundwater sample was collected from a tube well situated in a village of the indigenous community at Kangkar Senangar, Parit Sulong, Johor, with coordinates of 2°03'04.1"N 102°52'27.2". The surrounding area of the village is mostly palm oil plantations. The groundwater was pumped from the tube well to a faucet that was connected to the tube well by piping. Hence, the groundwater sample was collected from the faucet in a 5L high density polyethylene sampling bottle. The bottle was kept in a chiller room at the Environmental Engineering Technology Laboratory, Universiti Tun Hussein Onn Malaysia, Pagoh prior to the experiment conducted.

2.2 Groundwater Characterisation

The characteristics of the groundwater collected were analysed for water quality parameters, including pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), turbidity, total suspended solids (TSS), total dissolved solids (TDS), ammonia nitrogen (AN), total hardness (TH), and iron. The pH and DO concentration of the groundwater sample were measured using a HQ440d benchtop multi-meter (Hach, USA). The turbidity level of the groundwater sample was measured using a TL2300 Tungsten lamp turbidimeter (Hach, USA). The COD, AN, TH, and iron were measured using a DR6000 UV-VIS Spectrophotometer (Hach, USA), while testing for BOD, TSS, and TDS were conducted according to the APHA Standard Methods.

2.3 Characterisation of Plastic Waste and Commercial Resin

The plastic waste resin was obtained from a microelectronic industry located in Muar, Johor and commercial resin was purchased online. Fig. 1 shows the plastic waste and commercial resin. The plastic waste resin was thoroughly rinsed and cleaned with water before being used. Both resins were characterized via scanning electron microscopy (SEM), energy dispersive X-ray (EDX), Fourier transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD) analysis. A COXEM SEM-EDX (EM-30AX) machine was used to analyze the surface morphology and elemental composition of the plastic waste and commercial resin. FTIR with ATR was conducted using the Spectrum Two™ PerkinElmer (USA) machine. The functional groups of the resin samples were investigated in the mid-infrared (IR) 4000–400 cm^{-1} region. An average of ten scans with a resolution of 4 cm^{-1} was obtained for each sample. X'Pert' Powder (Malvern Panalytical) was used to analyzed the crystalline characteristics and composition of the plastic waste and commercial resin.

(a)   **(b)**

Fig. 1 *Resin from (a) plastic waste; and (b) commercial*

2.4 Experimental Study of Ion Exchange Process Using Plastic Waste and Commercial Resin via Column Method

The performances of the plastic waste and commercial resin were evaluated in an experiment conducted via column method. An acrylic column with size of 30 x 9 x 9 cm was used in this study. The column was filled with resin, either plastic waste or commercial resin for each experiment. The setup of the experiment is shown in Fig. 2. The collected groundwater sample was filled in the feed tank. Then, the valve of the tank was opened to allow the groundwater to flow into the column by gravity. The groundwater was treated by the resin in the column through the ion exchange process. The effect of different loadings of plastic waste and commercial resin used in the experiment (Table 1) was investigated on the groundwater treatment. The water quality parameters were tested before and after the treatment, including pH, turbidity, DO, BOD, COD, AN, TSS, TDS, TH, and iron concentration. The removal rate of the treatment process was calculated using Equation 1 for parameters such as BOD, COD, TSS, TDS, AN, TH, and Iron:

$$\text{Removal rate } (\%) = \frac{(C_i - C_f)}{C_i} \times 100 \qquad (1)$$

Where:
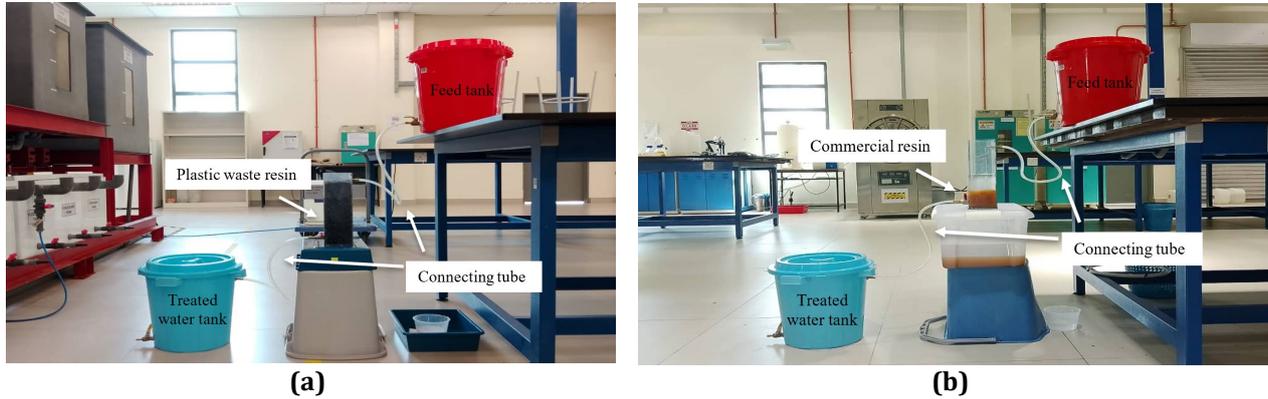C_i = initial concentration
C_f = final concentration

Fig. 2 *Setup of experiment for (a) plastic waste; and (b) commercial resin*

Table 1 *Different loadings of plastic waste and commercial resin used in the experiment*

Dosage (cm³)	Plastic waste resin (g)	Commercial resin (g)
721	600	509
1442	1400	719
2163	2100	1048

3. Results and Discussion

3.1 Characteristics of Plastic Waste and Commercial Resin

The results for the characteristics of the plastic waste and commercial resin, including surface morphology, elemental composition, functional groups, and X-ray diffraction pattern, are discussed in detail in the following subsection.

3.1.1 Surface Morphology and Elemental Composition

The surface morphology of the commercial and plastic waste resin is shown in Fig. 3. The commercial resin in Fig. 3(a) has a uniform, smooth surface, and spherical beads that enhance the packing density in filtration columns. The refined structure of commercial resins ensures durability and stability during the ion exchange process, making them more dependable for long-term use [22]. The surface morphology directly impacts the efficiency of the ion exchange process, making it more efficient. Commercial resins are also more durable and less prone to physical degradation, ensuring consistent performance over time [23]. As for the surface morphology of plastic waste resin in Fig. 3(b), it exhibits irregularities, rough textures, and uneven distribution, indicating its heterogeneous nature. The surface porosity of the plastic waste resin varies, with irregular distribution of pores and voids that can increase the surface area for the ion exchange process. The cracks and fissures, resulting from mechanical stress, environmental degradation, or recycling, may increase the surface area but can weaken material structural integrity [24].

Fig. 4 shows the elemental composition of the commercial and plastic waste resin. The elemental composition of the commercial resin consists of 39.63% carbon, 38.17% oxygen, 10.57% sodium, 9.16% sulfur, and 2.48% silicon. On the other hand, the elemental composition for plastic waste resin consists of 49% oxygen, and 51% silicon. The composition of commercial resin is high in carbon content that may provide the selectivity for ion exchange process with contaminants [25]. Carbon-rich materials often contribute to hydrophobic regions in the resin, which influence interactions with specific contaminants. These materials also enable functional groups like sulfonic or amine groups to interact with contaminants more effectively based on electrostatic interactions and

ionic sizes. This selectivity plays a critical role in softening process where calcium and magnesium ions are captured and held by the resin, while sodium or potassium ions are released into the water in their place, resulting in softened water [25]. Meanwhile, plastic waste resin has high silicon content that contributes to the ion exchange process primarily through the presence of silanol (Si-OH) groups on its surface. These groups can function as weak acidic sites that interact with cations during ion exchange [27]. Silanol groups are capable of undergoing ionization, especially under certain pH conditions, forming negatively charged sites that attract positively charged ions such as Ca^{2+} and Mg^{2+} [28]. This interaction allows the resin to selectively remove these ions from solutions [29].
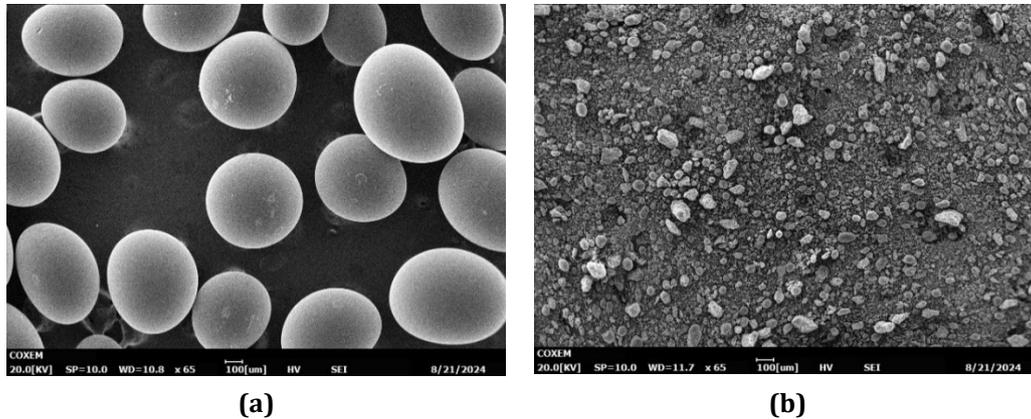

(a) **(b)**

Fig. 3 *Surface morphology of (a) commercial; and (b) plastic waste resin at 65x magnification*
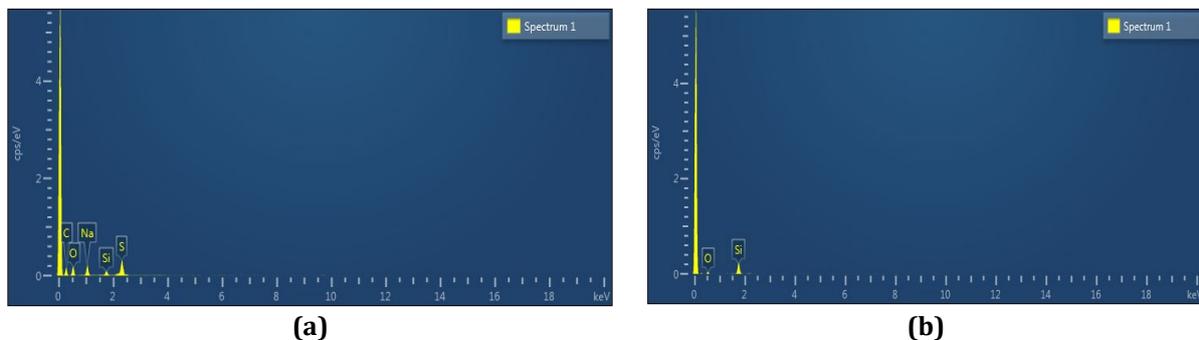

(a) **(b)**

Fig. 4 *Elemental composition of (a) commercial; and (b) plastic waste resin*

3.1.2 Functional Groups

Fig. 5 shows the FTIR spectra of the commercial and plastic waste resin. For the commercial resin in Fig. 5(a), the peaks at 870.50 cm^{-1} and 796.81 cm^{-1} are associated with bending vibrations of C-H bonds in alkenes or aromatic compounds. The peak at 655.82 cm^{-1} is attributed to bending vibrations in aromatic compounds. The peak at 1091.10 cm^{-1} is associated with C-O stretching vibrations typical of alcohols, ethers, or esters, suggesting the presence of organic functional groups. While this peak could potentially indicate siloxane (Si-O-Si) bonds, the low silica content observed in the EDX analysis points more strongly to organic C-O functionalities rather than silicon-based structures [30]. The peak at 455.14 cm^{-1} is linked to bending vibrations of C-O-C bonds or C-OH, further supporting the presence of alcohols or ethers instead of silicates or another silicon-containing compound. C–H is a single covalent bond between a carbon atom and a hydrogen atom while C-O is single covalent bond between a carbon and an oxygen atom and C-O-C is an oxygen atom bonded to two carbon atoms which characterized the structure of an ether. Additionally, sulfonic acid groups (–SO_3H), which are often present in ion-exchange resins, exhibit S=O stretching vibrations around 1160–1200 cm^{-1}, overlapping with C-O stretches [30].

The FTIR spectra for plastic waste resin in Fig. 5(b) shows the peak at 3428.32 cm^{-1} attributed to O-H stretching vibrations, indicating hydroxyl groups. The peak 2923.46 cm^{-1} corresponds to C-H stretching vibrations in alkanes, indicating long carbon chains. The peak, 2016.67 cm^{-1}, may indicate complex molecular structures potentially involving vibration modes of C=C bonds or conjugated systems. These could be indicative of aromatic groups or conjugated double bonds within the resin. These groups could also play a role in enhancing

the resin's ability to adsorb certain organic contaminants or facilitate ion exchange through π-interactions or other mechanisms. The peak at 1633.86 cm⁻¹ is C=O stretching vibrations related to carbonyl groups [32].
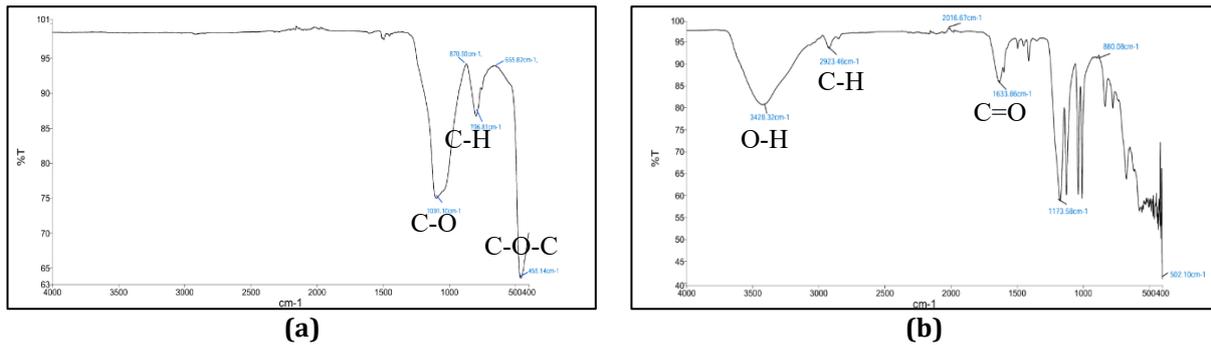

Fig. 5 *FTIR spectra of (a) commercial; and (b) plastic waste resin*

3.1.3 X-ray Diffraction Pattern

Fig. 6 shows the X-ray diffraction (XRD) pattern of the commercial and plastic waste resin. The XRD pattern of the commercial resin in Fig. 6(a) shows various peaks centered at 19, 23, and 25. There are subtle shifts in peak positions and intensities, indicating the successful incorporation of functional groups onto the resin surface. The disappearance of sharp peaks typically associated with the base polymer structure confirms the presence of functional groups [28]. For plastic waste resin, the highest peak 23 in Fig. 6(b) confirms the high silicon content in the plastic waste. This peak is typically associated with the bending vibrations of Si-O bonds, which are characteristic of crystalline forms of silica (SiO$_2$) or other silicon-containing materials. The intensity of this peak suggests a significant presence of crystalline silicon in the resin, highlighting its importance in contributing to the resin's structural and functional properties.
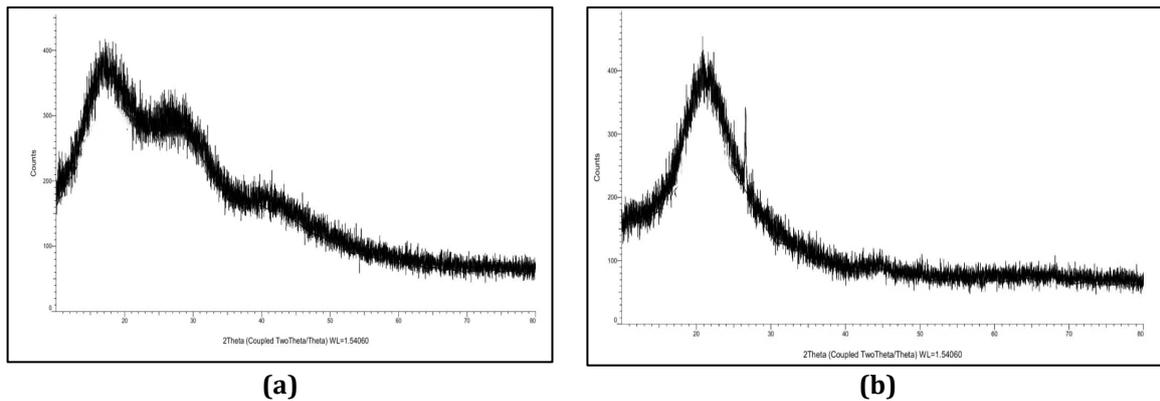

Fig. 6 *XRD patterns of (a) commercial; and (b) plastic waste resin*

3.2 Groundwater Treatment Using Commercial Resin and Plastic Waste Resin

The performance of commercial and plastic waste resins in groundwater treatment is summarised in Table 2. The commercial resin significantly outperformed the plastic waste resin in contaminant removal, achieving high removal rates across multiple parameters. Specifically, the commercial resin reduced BOD, TSS and COD by 98.6%, 88.9%, and 85%, respectively. Additionally, it removed 66% iron, 50% TDS, 47.2% AN, and 44% TH, demonstrating its ability to effectively treat groundwater and produce safe, clean water. This could be due to the large surface area and the presence of specific functional groups like sulfonic acid (-SO$_3$H), which is known to effectively bind and remove both organic and inorganic contaminants from the groundwater. The electrostatic and hydrophobic interactions facilitated by this functional group are key mechanisms in the efficient removal of such contaminants. Moreover, the large surface area of the resin increases the number of available active sites for these interactions, improving the overall efficiency of the resin in water treatment applications [23]. In contrast, the plastic waste resin showed much lower efficiency, with only a 19.2% removal of COD and a 66.7% reduction in TSS. It failed to remove AN, TH, and iron effectively and even led to an increase in BOD levels, likely due to the leaching of organic compounds from the resin [33]. This limited performance suggests that the plastic waste

resin's treatment capacity was insufficient for treating the groundwater. Based on the National Groundwater Quality Standards for Conventional Drinking Water Treatment, the treated water using the commercial resin complied with most parameters, including COD (3.67 mg/L), BOD (0.04 mg/L), TDS (0.04 mg/L), AN (0.19 mg/L), and iron (0.53 mg/L), all within allowable limits. Turbidity slightly increased to 5.80 NTU but remained far below the maximum threshold of 1000 NTU. In contrast, the plastic waste resin exceeded COD (19.67 mg/L) and BOD (8.52 mg/L) limits, highlighting its inadequacy for meeting drinking water quality standards. Overall, the commercial resin proved far more effective, with superior contaminant removal efficiency and compliance with groundwater quality standards, making it suitable for high-standard water treatment applications [34]. Conversely, the plastic waste resin, while showing some reduction in TSS, exhibited limitations, particularly for BOD and COD removal.

Table 2 *Groundwater treatment using commercial and plastic waste resin*

Parameter	Before treatment	After treatment		National Groundwater Quality Standards for Conventional Drinking Water Treatment [35]
		Commercial resin	Plastic waste resin	
pH	7.16	6.73	6.06	5.5-9.0
DO (mg/L)	8.43	9.75	8.96	-
Turbidity (NTU)	5.54	5.80	5.60	1000
COD (mg/L)	24.33	3.67	19.67	10
BOD (mg/L)	2.88	0.04	8.52	6
TSS (mg/L)	18	2	6	-
TDS (mg/L)	0.08	0.04	0.06	1500
AN (mg/L)	0.36	0.19	0.38	1.5
TH (mg/L CaCO$_3$)	1.56	1.08	4.08	500
Iron (mg/L)	0.88	0.53	0.92	1.0

3.3 Effect of Different Loadings of Commercial and Plastic Waste Resin on Total Hardness Removal in Groundwater

Fig. 7 shows that, at 721 cm^3 dosage, the commercial resin reduced TH from 29.96 mg/L to 10.55 mg/L (64.77% removal), while the plastic waste resin only reduced it to 25.36 mg/L (15.36% removal). At 1442 cm^3 dosage, the commercial resin further reduced TH to 7.5 mg/L (74.95%), while the plastic waste resin reduced it to 18.3 mg/L (38.94%). At 2163 cm^3 dosage, the commercial resin achieved the highest removal, reducing TH to 2.5 mg/L (91.65%), while the plastic waste resin reduced it to 14.35 mg/L (52.12%). The commercial resin's superior performance is due to its functional groups and smooth, porous structure. The resins are highly efficient at exchanging harmful cations and anions with less harmful ones, thus purifying the water [36]. The lower performance of the plastic waste resin can be attributed to its possibly limited ion exchange capacity or inefficient removal of certain contaminants, such as multivalent ions [37].
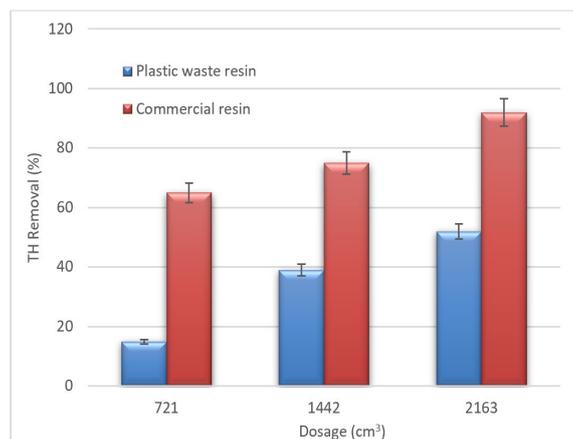

Fig. 7 *Effect of different loadings of commercial and plastic waste resin on TH removal*

3.4   Performance Comparison of Commercial and Plastic Waste Resin for Total Hardness Removal over Time

Fig. 8 compares the performance of commercial and plastic waste resins for TH removal over time. At the start, the groundwater had a TH concentration of 200 mg/L $CaCO_3$. After 4 hours, the commercial resin reduced the TH concentration to 2.5 mg/L (91.65% removal), while the plastic waste resin reduced it to 14.35 mg/L (52.12% removal). The commercial resin's superior performance is attributed to its optimized functional groups, porous structure, and higher cation exchange capacity, as indicated by FTIR, SEM, and EDX analyses. The performance trend shows that both resins progressively reduced TH over time, with the commercial resin achieving a steep reduction after 2 hours, likely due to its high affinity for Ca^{2+} and Mg^{2+} ions. The plastic waste resin, despite showing a similar trend, was less efficient due to its lower ion exchange capacity and lack of specific functional groups. The presence of competing ions in the groundwater may have also influenced the resin's efficiency. The results align with Abegunde et al. [38], highlighting the influence of contact time and water chemistry on ion exchange performance. The commercial resin demonstrated superior TH removal, reducing it from 160 mg/L to 2.5 mg/L after 4 hours, compared to 14.35 mg/L with the plastic waste resin.

The commercial resin's higher efficiency is due to optimized functional groups, porous morphology, and elemental composition, enhancing ion exchange capacity [39]. In contrast, plastic waste resins, made from materials like polyethylene, polypropylene and polystyrene lack the specialized functional groups and structural properties necessary for effective ion exchange, resulting in lower ion removal capacity. Competing ions in groundwater further reduce the efficiency of plastic waste resins [40]. Overall, the commercial resin is significantly more effective for TH removal.
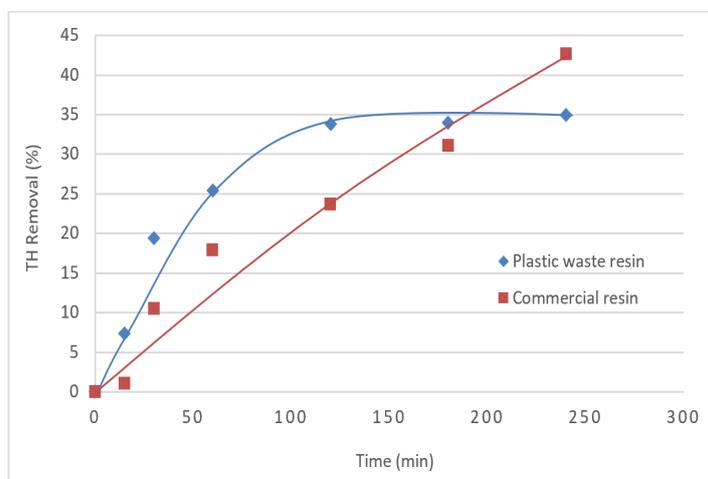

Fig. 8 *Performance comparison between commercial and plastic waste resin for TH removal over time*

4. Conclusion

This study evaluated the effectiveness of commercial and plastic waste resins for groundwater treatment. The commercial resin exhibited a smooth, uniform surface, whereas the plastic waste resin had a rough, irregular morphology. Elemental analysis using EDX confirmed the presence of carbon, oxygen, and silicon in both resins. FTIR spectroscopy identified key functional groups, including hydroxyl and sulfonic acid groups. XRD analysis indicated that the commercial resin was predominantly amorphous, while the plastic waste resin possessed fewer effective functional groups, limiting its ion exchange efficiency. In column studies, the commercial resin demonstrated superior contaminant removal, achieving 98.6% BOD removal, 85% COD removal, and 88.9% TSS removal. In comparison, the plastic waste resin showed lower performance, with only 66.7% TSS and 19.2 % COD removal. At a dosage of 2163 cm^3, the commercial resin achieved 91.65% TH removal, while the plastic waste resin reached only 52.12%. Overall, the commercial resin outperformed the plastic waste resin in groundwater treatment. Despite its current limitations, the plastic waste resin presents a promising low-cost and sustainable alternative, especially for applications where high removal efficiency is not critical. With further modification such as surface activation, functional group grafting, or blending with other materials, its ion exchange capacity could be significantly enhanced. Future work should explore chemical treatments or composite formulations to improve its structure and reactivity. Additionally, the resin could be applied in preliminary treatment stages or in decentralized water treatment systems where cost constraints are a key consideration.

Acknowledgement

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** *Nur Naqiyah Yunus, Mimi Suliza Muhamad; Farhan Mohd Mukelas;* **data collection:** *Nur Naqiyah Yunus;* **analysis and interpretation of results:** *Nur Naqiyah Yunus, Mimi Suliza Muhamad; Noorul Hudai Abdullah;* **draft manuscript preparation:** *Nur Naqiyah Yunus, Mimi Suliza Muhamad; Norshuhaila Mohamed Sunar. All authors reviewed the results and approved the final version of the manuscript.*

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