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Bio-Based Ion Exchange Resin from Water Hyacinth for Efficient Groundwater Hardness Treatment

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Abstract

This study aims to prepare cation exchange resin from the stems and leaves of water hyacinth via the sulfonation process and to evaluate their efficiency and capacity for water softening. The water hyacinth was separated into stems and leaves and was then ground to powder. The powders were subjected to sulfuric acid treatment (sulfonation) to introduce active sulfonic acid ($-\text{SO}_3\text{H}$) groups. Treated materials were classified as stem- and leaf-derived water hyacinth resin. The results revealed that sulfuric acid-treated water hyacinth enhanced the porosity of resin due to the incorporation of sulfonic acid groups. This improvement provided a larger surface area and more active sites for cation exchange compared to untreated samples. Sulfuric acid-treated water hyacinth leaves demonstrated greater hardness removal efficiency compared to stems, attributed to the higher cellulose content in the leaves. The optimal dosage of leaf-derived resin for complete hardness removal ($414 \text{ mg}\cdot\text{L}^{-1}$ as CaCO_3) was determined to be $22.5 \text{ g}\cdot\text{L}^{-1}$, equivalent to an ion exchange capacity of $0.810 \text{ meq}\cdot\text{g}^{-1}$. The resin exhibited selective affinity for ions in the order of $\text{Mg}^{2+} > \text{Ca}^{2+} \gg \text{Na}^+$. Additionally, the resin retained its efficiency after the first and second regeneration cycles using 0.01 M hydrochloric acid, maintaining 100% hardness removal, comparable to the performance of the new resin. These results highlight the potential of bio-based resins derived from water hyacinth leaves as a sustainable, cost-effective solution for water softening. Bio-based resins contribute to environmental conservation, promote eco-friendly materials, and support the circular economy and sustainable resource management principles.

Keywords: Bio-based materials, Cation exchange resin, Groundwater, Hardness removal, Water hyacinth.

1. Introduction

Water hyacinth (*Eichhornia crassipes*) is an invasive aquatic plant that grows rapidly, particularly in tropical and subtropical freshwater ecosystems. Its uncontrolled growth poses significant ecological challenges, primarily due to its impact on aquatic environments. The extensive layer of water hyacinth reduces sunlight penetration into the water column, inhibiting the growth of submerged aquatic plants and disrupting photosynthesis, resulting in dissolved oxygen depletion. This hypoxic condition negatively affects aquatic organisms, ultimately decreasing biodiversity and disrupting ecosystem stability [1]. Moreover, the decomposition of accumulated plant matter contributes to water quality deterioration by increasing nutrient concentrations, accelerating eutrophication, and exacerbating water pollution issues. From an economic perspective, excessive water hyacinth growth obstructs waterways, impedes navigation, interferes with hydroelectric power operations by clogging turbines and intake structures, leading to increased maintenance costs [2]. Although various control measures, including mechanical removal, biological interventions, and chemical treatments, have been implemented, their effectiveness is often limited by requiring significant labour, financial investment, and ongoing management to prevent regrowth [3].

To address these challenges, researchers have explored sustainable applications of water hyacinth, including its use as raw material for biofuel production, composting, animal feed, and wastewater treatment [4]. Its high nitrogen and low lignin content enhance the conversion of hemicellulose into fermentable sugars, making it a

promising feedstock for bioethanol production [5]. Additionally, water hyacinth is rich in essential macronutrients including nitrogen, phosphorus, and potassium, which improve soil fertility when incorporated into composting systems [6]. It has also been studied as an alternative feed source for livestock and aquaculture due to its favourable amino acid composition and high protein content [7]. However, its tendency to adsorb heavy metals from contaminated water poses potential health risks, necessitating thorough assessment before its application in agriculture and animal nutrition [8]. Beyond its agricultural and bioenergy applications, water hyacinth is also used in the production of handicrafts. In Thailand, its stem fibres are utilized in weaving eco-friendly products such as bags, sandals, and mats [9]. However, the roots and leaves remain largely underutilized. Identifying appropriate methods for effective water hyacinth utilization is an ongoing research topic. Recent studies have focused on converting water hyacinth into bio-based materials, adsorbents, and resins. These approaches contribute to sustainable water hyacinth management by promoting resource management and waste valorization.

Groundwater serves as an essential resource for various purposes, including drinking water supply, domestic use, agriculture, and industrial applications. However, in some regions, such as Nakhon Ratchasima, Thailand, excessive groundwater hardness, exceeding $300 \text{ mg} \cdot \text{L}^{-1}$ as CaCO_3 , has raised significant concerns [10]. High water hardness presents challenges for household and industrial activities. It also poses potential health risks, including increased risks of cardiovascular diseases, kidney stones, and reproductive diseases after prolonged consumption [11]. Consequently, effective removal of hardness is necessary to ensure safe and high-quality water for consumption.

Water hardness primarily results from elevated concentrations of calcium ions (Ca^{2+}) and magnesium ions (Mg^{2+}). Permanent water hardness can be treated using chelating agents such as ethylenediaminetetraacetic acid (EDTA), ion exchange resins, or zeolite, while temporary hardness can be eliminated through boiling. Ion exchange using synthetic resins [12] and zeolite-based treatments [13] are among the most widely applied methods for water softening. Recently, the use of plant-based materials for water treatment has gained attention due to their natural biosorption properties. Biosorption provides a cost-effective and environmentally sustainable approach for removing hazardous heavy metals from industrial effluents while improving water quality. Several agricultural residues, including sugarcane bagasse [14], congress grass, rice husk, rape straw, sawdust, and eggshell [15], have been investigated for their adsorption capabilities. In addition, pinecone-based materials have been studied for ion exchange efficiency and their potential for regeneration and reuse as resin [16]. Additionally, previous research has demonstrated the potential of water hyacinth-derived resins for heavy metal removal, particularly in chromium (Cr) ion exchange [17]. Water hyacinth is particularly suitable for resin synthesis due to its high cellulose content, comprising approximately 45% of its biomass [17], making it a promising material for the development of environmentally friendly ion-exchange materials. However, research on water hyacinth-derived resins for water hardness removal remains limited.

Material modification has been demonstrated to enhance pollutant removal from water using strong acids (e.g., sulfuric acid), weak acids (e.g., acetic acid), or alkaline agents (e.g., sodium hydroxide) [16, 18]. Sulfuric acid treatment (sulfonation) is one of the most commonly utilized methods for functionalizing materials. This procedure involves adding sulfonic acid ($-\text{SO}_3\text{H}$) groups to the polymeric structure of materials. Sulfonic acid groups are strong acidic functional groups that operate as very efficient active sites in cation exchange resins [18]. Additionally, these groups readily dissolve in aqueous solutions, resulting in an excessive number of negatively charged sites. Sulfonic acid showed a greater affinity and exchange capacity for divalent ions (e.g., Ca^{2+} and Mg^{2+}) compared to weak acid functional groups, such as carboxyl groups, under a wide pH range. It therefore has high dissolution and ion exchange performance in many water treatment applications [12]. As a result, sulfonation is a practical and appropriate technique for generating bio-based resins from water hyacinth for water softening applications, due to the high ion exchange capacity and operating stability required throughout a wide range of conditions.

Previous studies have focused on the use of water hyacinth for sustainable purposes. It has been applied as a raw material for biofuel production, composting to improve soil fertility, animal feed, and as a biosorbent for wastewater treatment [5–8]. Many studies have primarily examined heavy metal adsorption. However, the ability of water hyacinth to synthesize ion-exchange resins has received limited attention, particularly for reducing water hardness. Water hyacinth contains a high amount of cellulose and is readily available. As a result, it is a promising raw material for the production of bio-based resins. This study focuses on the development of cation exchange resins from both stems and leaves of water hyacinth. The leaves are often underutilized, but they were valorized as a bio-based material in this study. A sulfonation process is used to introduce sulfonic acid ($-\text{SO}_3\text{H}$) groups. These strong acid groups enhance ion exchange capacity and selectivity toward hardness ions. This approach differs from previous studies that mainly focused on heavy metal removal. This study expands the application of water hyacinth to groundwater hardness treatment. It also evaluates removal efficiency, ion selectivity, ion exchange capacity, and regeneration performance. From a practical perspective, converting water hyacinth into reusable resins helps control this invasive plant in aquatic systems. It also provides a sustainable option for water treatment. The use of local biomass could reduce commercial synthetic resin use, water treatment costs, and environmental impact. Additionally, the water hyacinth-derived resins can be regenerated and reused.

Therefore, this study focuses on the synthesis and application of water hyacinth-based resin for groundwater hardness removal. The specific objectives are: (1) to prepare and characterize water hyacinth resin for water hardness removal and (2) to determine the efficiency of water hardness removal, ion selectivity, ion exchange capacity, and regeneration performance. The findings of this study are expected to contribute to the development of bio-based materials for water treatment, offering a sustainable and cost-effective alternative for water softening. This supports long-term application that aligns with circular economy principles through waste valorization. Furthermore, this research supports environmental conservation efforts by reducing waste, minimizing ecosystem pollution, and promoting eco-friendly water treatment technologies.

2. Materials and Methods

2.1 Materials

Groundwater samples were collected from the Saphanhin community near Suranaree University of Technology (SUT) in Nakhon Ratchasima, Thailand. Water hyacinth was obtained from the constructed wetland at the wastewater treatment system of SUT. Fresh samples were harvested during the dry season at approximately 4–6 weeks old and were characterized by large, thick leaves, swollen petioles, and prolific stolon development. The roots were first removed, and the stems and leaves were thoroughly washed with tap water to eliminate adhering impurities. The cleaned stems and leaves were then sun-dried for 2–3 days, followed by cutting into small pieces. Subsequently, the samples were dried in a hot air oven at 80 °C for 24 h to ensure complete moisture removal. The dried materials were then stored in zip-lock plastic bags and kept in a desiccator prior to use. The chemicals used in this study included sulfuric acid (96% H₂SO₄, Carlo-Erba), sodium hydroxide (97% NaOH, Carlo-Erba), ethanol (98% CH₃CH₂OH, Sigma-Aldrich), calcium carbonate (99% CaCO₃, Sigma-Aldrich), ethylenediaminetetraacetic acid (99% EDTA, Sigma-Aldrich), Eriochrome Black T (ACS reagent-indicator grade, Sigma-Aldrich), and hydrochloric acid (37% HCl, Carlo-Erba).

2.2 Water hyacinth resin (WHR) preparation

The dried-water hyacinth was ground into a fine powder and sieved using an 18-mesh sieve. For the resin preparation, the stem and leaf powder of the water hyacinth were subsequently treated with a sulfonation process, as described by Chamkrom (2003) [19]. Fifty grams of water hyacinth stem or leaf powder were digested with 100 mL of 14 N sodium hydroxide (NaOH) solution, stirred for 20 min in an ice bath, and then allowed to rest at room temperature for 30 min. Subsequently, 50 mL of sulfuric acid (H₂SO₄) was added, and the mixture was stirred for 20 min in a water bath maintained at 45°C. The treated samples were thoroughly washed with deionized water and ethanol to remove impurities and then dried at 80 °C for 24 hours. The final product was obtained as black material. The stem-derived resin was designated as WHSR, while the leaf-derived resin was labeled WHLR.

2.3 WHR characterization

The untreated stems and leaves of water hyacinth were analyzed for their morphology to serve as baseline data. Additionally, sulfonated WHSR and WHLR samples were examined to observe morphological changes resulting from the acidic treatment. The morphology of all samples was investigated using a Carl Zeiss Auriga Field Emission Scanning Electron Microscope (SEM) operated at an accelerating voltage of 5.00 kV with a secondary electron (SE) detector. A Leica EM ACE600 instrument was employed to prepare the samples for SEM analysis. To identify functional groups in the WHSR and WHLR samples, Fourier Transform Infrared Spectroscopy (FT-IR) analysis was performed. A Bruker Tensor 27 FTIR spectrometer with ATR mode was used to capture spectra in the range of 4000 to 400 cm⁻¹.

2.4 Activity of water hardness removal

The efficiency of water hardness removal, cation selectivity, and cation exchange capacity of water hyacinth resin were investigated. For efficiency of water hardness removal, two variables were examined: the effect of plant components (stem- or leaf-derived resin) and resin dosage. The amount of WHSR or WHLR at different dosages, including 2.5, 5.0, 7.5, 10.0, and 12.5 g·L⁻¹ was added to individual beakers. Then, 200 mL of groundwater was added into the beaker. The samples were stirred at 200 rpm using a magnetic stirrer at room temperature for 30 min. Afterward, the WHR was separated using a 0.45 µm syringe filter. The total hardness in raw and treated groundwater was determined using the EDTA titrimetric method, following the Standard Methods for the Examination of Water and Wastewater [20]. All experiments were carried out in triplicate.

For cation selectivity analysis, the better-performing resin (stem- or leaf-derived) was tested at 12.5 g·L⁻¹ with 200 mL of groundwater under the same stirring conditions as the hardness removal study. The removal efficiency

of specific cations (Na^+ , Mg^{2+} , and Ca^{2+}) in the groundwater was analyzed. The cation concentrations in raw and treated groundwater were measured using ion chromatography. The cation exchange capacity (CEC) of WHSR and WHLR was examined by mixing $5 \text{ g} \cdot \text{L}^{-1}$ of resin with 200 mL of 0.1 M NaCl solution. The samples were stirred at 200 rpm using a magnetic stirrer at room temperature for 30 min. The treated solution was filtered with a syringe filter and titrated with 0.1 M NaOH solution. The CEC was calculated in milliequivalents per gram ($\text{meq} \cdot \text{g}^{-1}$). The regeneration efficiency of better-performing resin (WHSR or WHLR) was determined using resin previously used for hardness removal (at $22.5 \text{ g} \cdot \text{L}^{-1}$). The resin was washed with distilled water and regenerated with 200 mL of 0.01 M HCl, stirred at 200 rpm for an hour. The resin was washed again with distilled water, dried at 80°C for 24 hours, and reused for hardness removal in the second and third cycles, following the method of Chawakitchareon and Sanguanduan (2003) [21]. All experiments were carried out in triplicate.

2.5 Statistical analysis

The statistical analysis in this study employed descriptive statistics to summarize data characteristics and variability. Results were reported as the average, standard deviation (S.D.), minimum, maximum, and number of samples (n). All experiments were conducted in replicate to ensure data reliability and reproducibility. To improve data quality and minimize the impact of outliers, analytical findings showing an efficiency deviation greater than 10% compared with replicate measurements were excluded from statistical calculations, and the experiments were repeated. This study employed only consistent data for result interpretation and discussion, ensuring robustness and reliability of the reported findings.

3. Results and Discussion

3.1 Characteristics of WHR

3.1.1 Morphology of WHR resin

The morphology of WHR (prepared from the stem and leaves of water hyacinth) was analyzed using a scanning electron microscope (SEM), and their SEM images are presented in Figure 1. The results revealed that the surface morphology of untreated water hyacinth stems and leaves exhibit a relatively smooth surface texture and fabric-like sheets with multiple layers as illustrated in Figure 1(A) and 1(B). Upon sulfuric acid treatment, the surface morphology of the stems and leaves underwent significant changes. The previously smooth surface transformed into an uneven texture with deep grooves and irregular patterns, attributed to the corrosive effects of sulfuric acid, as shown in Figure 1(C) and 1(D). The observed modifications are consistent with previous findings on the effects of acidic treatments on lignocellulosic materials. For instance, studies have demonstrated that acid hydrolysis may effectively remove lignin and hemicellulose, leading to surface erosion and increased porosity [22], [23]. These structural alterations are advantageous for applications such as ion exchange, which requires a highly porous structure to maximize interaction with ions in solutions. Consequently, the sulfonation of water hyacinth enhanced the porosity of the WHR materials, resulting in a larger surface area. Such morphological features are essential in ion exchange processes, because a higher surface area facilitates improved ion exchange capacity, thereby boosting the efficiency of the resin.

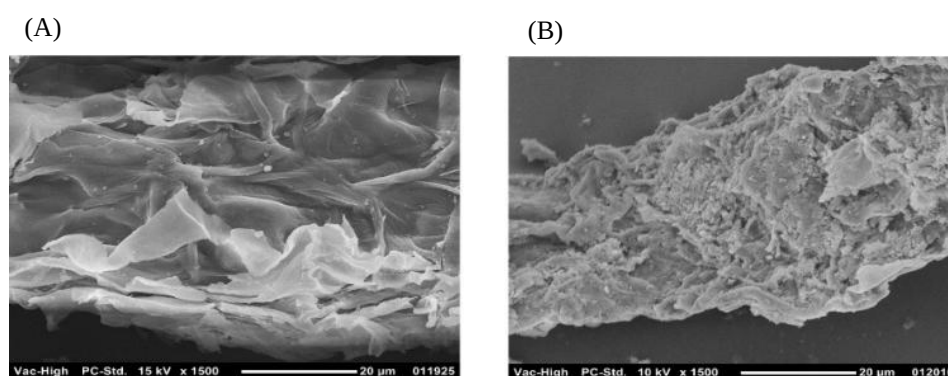


Figure 1 SEM images of the WHR morphology (A) water hyacinth stem, (B) sulfonated water hyacinth stem, (C) water hyacinth leaf and (D) sulfonated water hyacinth leaf.

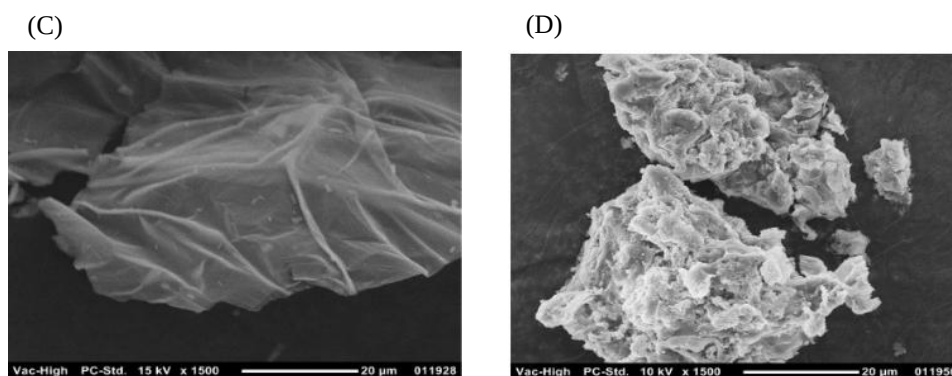


Figure 1 SEM images of the WHR morphology (A) water hyacinth stem, (B) sulfonated water hyacinth stem, (C) water hyacinth leaf and (D) sulfonated water hyacinth leaf. (Cont.)

3.1.2 FT-IR spectrum of WHR resin

The surface morphology of water hyacinth stems and leaves (PWHL) was analyzed using Fourier Transform Infrared Spectroscopy (FT-IR) to identify the functional groups present in the samples, as illustrated in Figure 2. The results revealed that, prior to sulfuric acid treatment, the FT-IR spectra of WHR displayed characteristic functional groups, including -OH stretching ($3400\text{--}3200\text{ cm}^{-1}$), C-H_n stretching ($2860\text{--}2970\text{ cm}^{-1}$), C=O stretching associated with ketones and carbonyls ($1717.8\text{--}1513.4\text{ cm}^{-1}$), and -O- ether stretching ($1488.7\text{--}1278.1\text{ cm}^{-1}$ and $1197.6\text{--}912.7\text{ cm}^{-1}$), as shown in Figure 2(A) and 2(C). These functional groups are indicative of the primary structure of cellulose [24]. Following sulfuric acid treatment, the FT-IR spectra, depicted in Figure 2(B) and 2(D), revealed the additional functional groups, including sulfonic acid group (-SO₃H) stretching at 1296 cm^{-1} , SO₂ asymmetric stretching (1382 cm^{-1}), and SO₃ symmetric stretching ($1500\text{--}1600\text{ cm}^{-1}$). This transformation highlights the introduction of sulfonic acid groups into the WHR surface structure as a result of the sulfonation process [18], [25]. The incorporation of sulfonic acid groups significantly improves the material's capacity to function as a cation exchange resin, allowing the removal of divalent cations such as calcium ions (Ca²⁺) and magnesium ions (Mg²⁺). Consequently, the modified PWHL demonstrates a strong potential for applications in water treatment as an effective cation exchange resin.

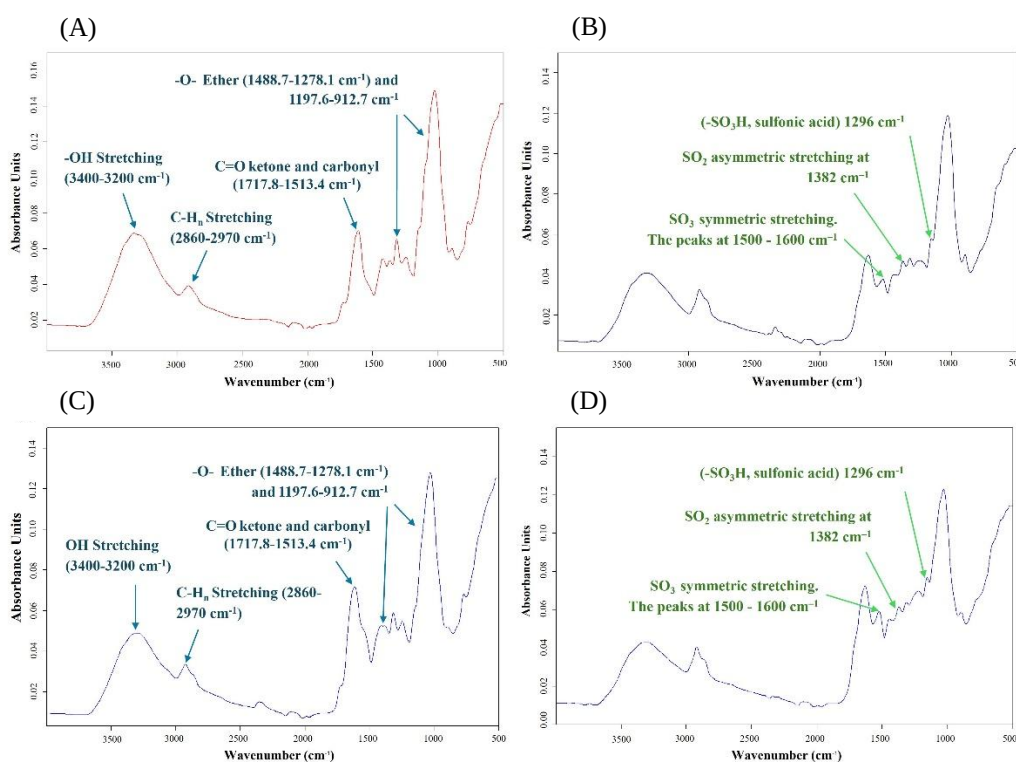


Figure 2 FT-IR spectrum of the water hyacinth powder (A) water hyacinth stem, (B) sulfonated water hyacinth stem (WHSR), (C) water hyacinth leaf and (D) sulfonated water hyacinth leaf (WHLR).

3.2 Water hardness removal using WHR resin

The efficiency of WHR resin for water hardness ion exchange was investigated in two aspects: (1) the effect of water hyacinth components used in resin synthesis and (2) the effect of resin dosage on ion exchange performance. The results and discussion are as follows:

3.2.1 Effect of plant component

This study evaluated the ion exchange efficiency of resins synthesized from sulfuric acid-treated stems and leaves of water hyacinth. The resins were used to treat groundwater with a total hardness of approximately $414 \text{ mg}\cdot\text{L}^{-1}$ as CaCO_3 . The efficiency of hardness removal using resins derived from the stems and leaves is presented in Figure 3. The results revealed that WHSR achieved average ion exchange efficiencies of 22.19%, 26.18%, 37.94%, 45.59%, and 70.29% at resin dosages of 2.5, 5, 7.5, 10, and $12.5 \text{ g}\cdot\text{L}^{-1}$, respectively. In comparison, WHLR demonstrated superior performance, with average ion exchange efficiencies of 23.18%, 39.65%, 52.07%, 67.93%, and 79.31% at the same dosages. The results indicate that sulfuric acid-treated water hyacinth leaves are more successful at hardness reduction than the stems. This enhanced performance can be attributed to the higher cellulose content in the leaves compared to those of stems. According to Barua and Kalamdhad (2017) [26], water hyacinth leaves contain approximately 30.9% cellulose, whereas the stems comprise 27.1%. Cellulose functions as a structural matrix that facilitates the attachment of functional groups, increasing the ion exchange capacity of the resin. The greater cellulose content in leaves likely offers the incorporation of sulfonic acid and other active functional groups during acidic treatment. These functional groups play a critical role in the ion exchange process, enabling effective interaction with hardness ions such as Ca^{2+} and Mg^{2+} [25]. Additionally, the porous structure of WHLR may increase its efficiency by providing more active sites for ion exchange. These findings emphasize the importance of selecting appropriate plant components for synthesizing bio-based resins for water treatment applications.

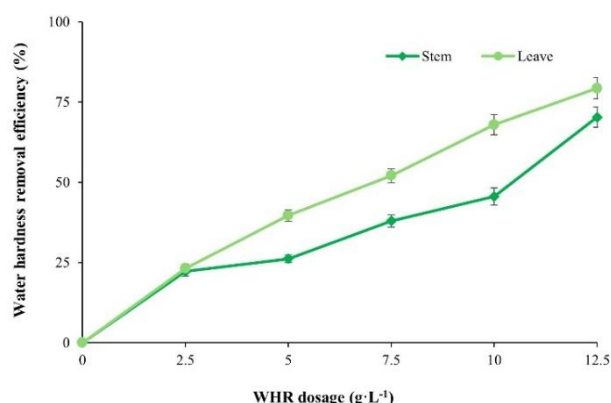


Figure 3 Efficiency of water hardness removal using sulfonated WHR derived from different plant components.

3.2.2 Effect of water hyacinth resin dosage

Given the superior performance of WHLR compared to WHSR for hardness removal, this section discusses the effect of leaf-derived water hyacinth resin dosages. The results revealed that the WHLR at dosages of 2.5, 5, 7.5, 10, 12.5, 17.5, 22.5, 27.5, and $32.5 \text{ g}\cdot\text{L}^{-1}$ achieved average hardness removal efficiencies of 23.18%, 39.65%, 52.07%, 67.93%, 79.31%, 92.94%, 100%, 100%, and 100%, respectively, as illustrated in Figure 4. This finding demonstrates that the optimal dosage of leaf-derived water hyacinth resin for complete hardness removal was $22.5 \text{ g}\cdot\text{L}^{-1}$, achieving a 100% efficiency in hardness removal, equivalent to 18.41 mg of hardness ions removed per gram of resin. The plateau in efficiency at increasing dosages suggests that at $22.5 \text{ g}\cdot\text{L}^{-1}$, the sulfonated WHLR provides sufficient active sites to interact with all hardness ions present in the solution. The high cellulose content allows for the additional insertion of active functional groups, including sulfonic acid groups, which are necessary for ion exchange activities. Increasing the dosage beyond this point does not enhance efficiency because the available ions in the water have been completely exchanged.

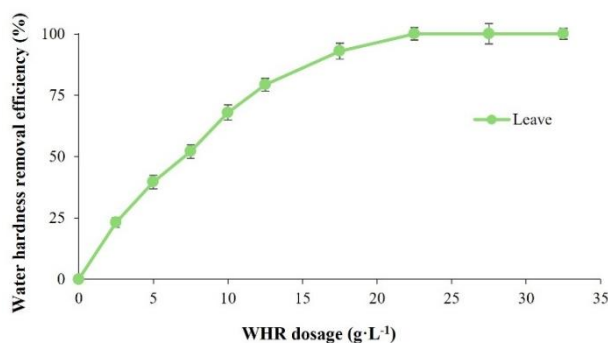


Figure 4 Efficiency of water hardness removal using different dosage of sulfonated water hyacinth resin.

3.3 Cation selectivity of WHR

To evaluate the ion-specific selectivity of the WHLR for ion exchange, the concentrations of three cations commonly present in the water were examined, including Na^+ , Mg^{2+} , and Ca^{2+} . The results of the ion-specific exchange efficiency are summarized in Table 1.

Table 1 Concentrations of cations in groundwater before and after hardness removal using WHLR.

Ion type	Ion concentration ($\text{mg}\cdot\text{L}^{-1}$)		Ion removal efficiency (%)
	Before	After	
Na^+	125.34 ± 0.49	122.10 ± 0.36	2.58 ± 0.19
Mg^{2+}	22.73 ± 0.25	14.04 ± 0.09	38.23 ± 0.32
Ca^{2+}	44.47 ± 0.03	30.88 ± 0.08	30.56 ± 0.16

Remark: resin dosage = $12.5 \text{ g}\cdot\text{L}^{-1}$

raw water pH = 8.10

after treatment pH = 7.12

As shown in Table 1, the resin exhibited the highest ion exchange efficiency for Mg^{2+} , with a removal rate of 38.23%, followed by Ca^{2+} at 30.56% and Na^+ at 2.58%. These findings indicate that the WHLR is particularly effective in exchanging $\text{Mg}^{2+} > \text{Ca}^{2+} \gg \text{Na}^+$. This behavior is attributed to the resin's functional groups, such as H^+ ions derived from sulfonic acid groups, which demonstrate a higher affinity for divalent cations such as Mg^{2+} and Ca^{2+} compared to monovalent cations such as Na^+ [27], [28]. Additionally, the experimental results were found that the ion exchanged during the water hardness reduction is H^+ , which corresponds to the observed decrease in pH from original 8.12 to 7.12 after treatment. This pH drop is caused by the release of H^+ ions from the resin during the ion exchange process.

The selectivity for Mg^{2+} and Ca^{2+} can also be explained by the dependence of the ion exchange process on charge density and hydration energy. Divalent cations (Mg^{2+} and Ca^{2+}) have higher charge densities than those of monovalent cations (Na^+), resulting in stronger electrostatic interactions with the negatively charged sulfonic acid groups in the resin matrix. Furthermore, divalent cations are less hydrated than monovalent ions, which increases their affinity for the resin's exchange sites [29]. This selectivity makes the WHLR especially suitable for water softening applications for Mg^{2+} and Ca^{2+} removal, such as in the treatment of groundwater or industrial water streams.

3.4 Ion exchange capacity of WHR

3.4.1 WHR capacity for water hardness removal

To further validate the ion exchange capacity of resins prepared from different components of acid-treated water hyacinth, the ion exchange capacities of the WHSL and WHRL were determined. The resins were evaluated by ion exchange with a 0.1 M NaCl solution and subsequently titrated with a 0.1 M NaOH solution. The results revealed that the WHLR has a higher IEC ($0.810 \pm 0.020 \text{ meq}\cdot\text{g}^{-1}$) compared to the WHSR ($0.685 \pm 0.013 \text{ meq}\cdot\text{g}^{-1}$), as shown in Figure 5. This difference in CEC is consistent with the previously observed greater efficiency of the leaf-derived resin in reducing water hardness in Section 3.2.1. Additionally, the higher IEC demonstrates that the leaf-derived resin has more active sites available for exchanging hardness-causing ions such as Mg^{2+} and Ca^{2+} , which supports its suitability for water treatment applications [30]. These findings confirm that the WHLR prepared through strong acid treatment exhibits a superior ion exchange capacity compared to the stem-derived resin, making it more effective for water hardness removal.

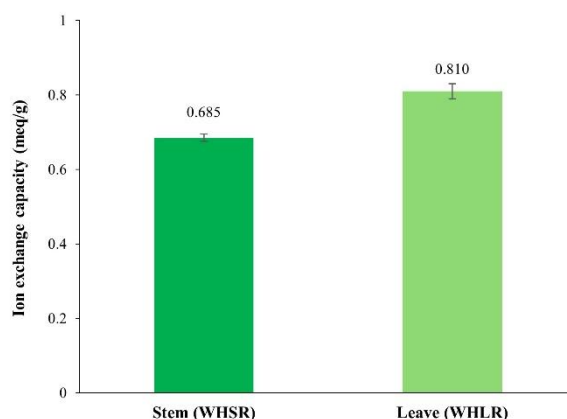


Figure 5 Water hyacinth resin capacity for water hardness removal

3.4.2 WHR capacity for water hardness removal after regeneration

This study evaluated the ion exchange efficiency of groundwater hardness removal utilizing regenerated resin prepared from sulfonated WHLR. The sulfonated WHLR retained its effectiveness, achieving $99.88\% \pm 0.08$ and 99.65 ± 0.13 hardness removal (at $22.5 \text{ g}\cdot\text{L}^{-1}$) after the first and second regeneration cycles, respectively, comparable to the performance of new resin ($99.98\% \pm 0.03$). These findings highlight the appropriateness of acid-treated WHLR resin for successful groundwater hardness reduction, as well as its potential for reuse after regeneration. The high regeneration efficiency is attributed to the strong acid functional groups, such as sulfonic acid, which remain intact during the ion exchange and regeneration processes [31]. This characteristic ensures that the resin retains its ion exchange capacity even after multiple cycles, making it a sustainable and cost-effective solution for water treatment applications. The ability to regenerate the resin also significantly reduces the environmental and economic expenses involved with its disposal and replacement. Compared to conventional synthetic ion exchange resins, bio-based resins derived from agricultural waste, such as water hyacinth, provide a promising alternative that adheres to the principles of circular economy and sustainable resource management [32].

3.4.3 Water hyacinth-based material for metal removal

Several studies have been conducted on water hyacinth-based materials for metal removal. Table 2 summarizes the information with an emphasis on preparation techniques, applications, and efficiency. The results demonstrated that two major types of materials were employed to remove metal from wastewater, including adsorbent (activated carbon) and ion exchange resin. The effectiveness of water hyacinth-based products was determined by testing a variety of metals. Untreated water hyacinth roots exhibited a removal capacity of $22.7 \text{ mg}\cdot\text{g}^{-1}$ for Cu^{2+} [33]. Thermally activated materials enhanced metal adsorption efficiency. Water hyacinth-derived activated carbon had Cd^{2+} adsorption capacities of 9.08 and $11.84 \text{ mg}\cdot\text{g}^{-1}$ for root- and leaf-based activated carbon, respectively [34]. For ion exchange resin, water hyacinth-based ion exchange resins exhibited encouraging results, with the citric acid-modified resin removing $23.38 \text{ mg}\cdot\text{g}^{-1}$ of Cr^{3+} . However, regeneration efficiency decreased dramatically after the first cycle [17]. Sulfonated water hyacinth leaf-derived resin (WHLR) successfully removes Ca^{2+} and Mg^{2+} (water hardness) from groundwater at $18.41 \text{ mg}\cdot\text{g}^{-1}$ and maintains 100% hardness removal effectiveness after the second regeneration cycle. This emphasizes WHLR's potential as a sustainable and reusable water softening material. The findings highlight the relevance of material modification in improving performance and the promise of water hyacinth-based materials for metal removal, particularly WHLR for groundwater treatment due to its superior regeneration capability.

When compared with other bio-based resins, WHLR has a moderate ability to remove water hardness while maintaining greater regeneration stability. The modified pine cone resin treated with citric acid has a higher capacity of $70.40 \text{ mg}\cdot\text{g}^{-1}$ ($1.41 \text{ meq}\cdot\text{g}^{-1}$). After ten cycles, its generation efficiency has reduced to about 90% [16]. Sugarcane bagasse treated with 10 mM of citric acid with microwave radiation removed Ca^{2+} at a higher capacity ($165 \text{ mg}\cdot\text{g}^{-1}$) in 20 minutes, but no generation data was recorded [14]. This limits its application for repeated usage. Natural zeolite treated with 1 M NaCl had a lower water hardness removal efficiency at $11.1 \text{ mg}\cdot\text{g}^{-1}$. 80% efficiency was found after the first-generation cycle under extreme conditions (3 M NaCl at 90°C) [13]. This regeneration capacity indicates decreased reusability compared to WHLR. The commercial synthetic resin demonstrates high hardness removal efficiency at $89.38 \text{ mg}\cdot\text{g}^{-1}$. It also retained more than 90% efficiency after three regeneration cycles with NaCl [35]. This confirms its effectiveness as a benchmark material. Nonetheless,

WHLR offers a competitive alternative, as it achieves complete regeneration at low acid concentration. The water hyacinth-based resin is derived from an abundant biowaste material, thereby reducing material cost and environmental impact.

Table 2 Preparation techniques, applications, and efficiency of water hyacinth-based materials for metal removal

Materials	Preparation	Application	Efficiency		Reference
			Removal capacity	Regeneration	
water hyacinth roots	untreated	adsorption Cu^{2+} in synthetic wastewater	$22.7 \text{ mg} \cdot \text{g}^{-1}$ in 2 hr.	-	[33]
water hyacinth activated carbon	thermal process at 300°C with 10% ZnCl_2	adsorption Cd^{2+} in synthetic wastewater	$9.08 \text{ mg} \cdot \text{g}^{-1}$ (root) and $11.84 \text{ mg} \cdot \text{g}^{-1}$ (leaves) in 8 hr.	-	[34]
water hyacinth derived resin	catalytic esterification of cellulose and citric acid	ion exchange Cr^{3+} in synthetic wastewater	$23.38 \text{ mg} \cdot \text{g}^{-1}$ in 1 hr. ($4.49 \text{ meq} \cdot \text{g}^{-1}$)	0.25 M nitric acid, <45% adsorption efficiency after first cycle	[17]
water hyacinth leave-derived resin (WHLR)	sulfuric acid treatment (sulfonation process)	ion exchange Ca^{2+} and Mg^{2+} in groundwater	$18.41 \text{ mg} \cdot \text{g}^{-1}$ in 1 hr. ($0.81 \text{ meq} \cdot \text{g}^{-1}$)	0.01 M HCl, 100% hardness removal after second cycle	This work
modified pine cone	0.6 M citric acid	ion exchange Ca^{2+} and Mg^{2+} in tap water from deep wells	$70.40 \text{ mg} \cdot \text{g}^{-1}$ in 12 hr. ($1.41 \text{ meq} \cdot \text{g}^{-1}$)	0.1 M HCl, ~90% removal efficiency after 10 cycle	[16]
sugarcane bagasse	10 mM of citric acid with microwave radiation	adsorption Ca^{2+} from groundwater	$165 \text{ mg} \cdot \text{g}^{-1}$ in 20 min.	-	[14]
natural zeolite	1 M NaCl	ion exchange Ca^{2+} , Mg^{2+} , and total hardness in groundwater	$11.1 \text{ mg} \cdot \text{g}^{-1}$ in 1 hr.	3M NaCl and 90°C , 80% removal efficiency after first cycle	[13]
commercial synthetic resin	untreated	ion exchange total hardness in domestic water supply	$89.38 \text{ mg} \cdot \text{g}^{-1}$ in 3 hr.	NaCl, >90% removal efficiency after third cycle	[35]

Remark: (-) = not regeneration

4. Conclusion

Sulfuric acid-treated water hyacinth demonstrated enhanced porosity and cation exchange efficiency due to the presence of sulfonic acid groups. The leaf-derived resin exhibited approximately 10% higher ion-exchange efficiency than the stem-derived resin. The optimal dosage for complete water hardness removal from groundwater ($414 \text{ mg} \cdot \text{L}^{-1}$ as CaCO_3) was $22.5 \text{ g} \cdot \text{L}^{-1}$, equivalent to 18.41 mg of hardness ions removed per gram of resin. The resin showed the most ion selectivity of Mg^{2+} and Ca^{2+} . After two regeneration cycles, the resin maintained 100% efficiency, confirming its reusability and potential as a sustainable solution for water softening. Importantly, this study highlights the development of ion exchange resin from the stems and leaves of water hyacinth, a locally abundant biowaste material. The results presented a water hardness removal performance comparable to commercial synthetic resins while being economically feasible and more environmentally friendly. This accomplishment demonstrates the high potential of water hyacinth-based resin as a sustainable alternative to water softening technologies. For further research, studies should optimize synthesis conditions to improve ion exchange capacity. The performance of the resin should be evaluated in continuous and pilot-scale systems. Long-term stability over multiple regeneration cycles should be systematically examined. Cost analysis and life cycle assessment should also be conducted. These directions will support the development and practical application of water hyacinth as bio-based resins in real water treatment systems.

5. Authors contribution

Yada Pinatha: Conceptualization, Investigation, Formal analysis, Data curation, Visualization, Writing – original draft and editing. Nichakorn Pornnongsan: Conceptualization, Investigation, Methodology, Data curation, Writing – review and editing. Apatsara Krasaesat: Conceptualization, Investigation, Methodology, Data curation, Writing – review and editing. Suwanan Juangjun: Investigation, Methodology, Data curation, Writing – review and editing. Saitarn Pakakaew: Investigation, Methodology, Data curation, Writing – review and editing. Praphaphon Thaochampa: Investigation, Methodology, Data curation, Writing – review and editing. Wina

Rongchapo: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Writing – review and editing, Supervision.

6. References

- [1] Nam TS, Cong NV, Thao HV. Enhancing renewable energy production from water hyacinth (*Eichhornia crassipes*) by a biogas-aerating recirculation system: A case study in the Vietnamese Mekong Delta. *Case Stud Chem Environ Eng*. 2023;7:100340.
- [2] Villamagna AM, Murphy BR. Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): A review. *Freshw Biol*. 2010;55:282–298.
- [3] Ayanda OI, Ajayi T, Asuwaju FP. *Eichhornia crassipes* (Mart.) Solms: Uses, challenges, threats, and prospects. *Sci World J*. 2020;2020:3452172.
- [4] Nega DT, Ancha VR, Manenti F, Adeel Z. A comprehensive policy framework for unlocking the potential of water hyacinth in Ethiopia's circular bioeconomy. *J Clean Prod*. 2024;435:140509.
- [5] Ofoefule A, Uzodinma E. Biogas production from blends of cassava (*Manihot utilissima*) peels with some animal wastes. *Int J Phys Sci*. 2009;4:398–402.
- [6] Serafini LF, Arrobas M, Rodrigues MÂ, Feliciano M, Miguens F, Oliveira V, et al. The composting of water hyacinth: A life cycle assessment perspective. *Waste Biomass Valor*. 2025;16:507–523.
- [7] Rajan PGR, Jona Esther S, Dhinakaran S, Dinesh J, Deepika R, Aruna S, et al. Water hyacinth: A sustainable source of feed, manure and industrial products: A review. *Agric Rev*. 2023;44(3):389–392.
- [8] Rezanian S, Ponraj M, Talaiekhozani A, Mohamad SE, Md Din MF, Taib SM, et al. Perspectives of phytoremediation using water hyacinth for removal of heavy metals, organic and inorganic pollutants in wastewater. *J Environ Manage*. 2015;163:125–133.
- [9] Thailand Foundation. Water hyacinth fiber products project [Internet]. 2020 [cited 2025 Jan 29]. Available from: <https://www.thailand-foundation.com/projects/water-hyacinth-fiber-products>
- [10] Pentamwa P, Thipthara W, Nuangon S. Removal of hardness from groundwater by synthetic resin from waste plastics. *Int J Environ Sci Dev*. 2011;2(6):479–483.
- [11] Sengupta P. Potential health impacts of hard water. *Int J Prev Med*. 2013;4(8):866–875.
- [12] Fathy M, Moghny TA, Mousa MA, El-Bellihi AAA, Awadallah AE. Sulfonated ion exchange polystyrene composite resin for calcium hardness removal. *Int J Emerg Technol Adv Eng*. 2015;5(11):20–29.
- [13] Hailu Y, Tilahun E, Brhane A, Resky H, Sahu O. Ion exchange process for calcium, magnesium and total hardness from groundwater with natural zeolite. *Groundw Sustain Dev*. 2019;8:457–467.
- [14] Soliman EM, Ahmed SA, Fadl AA. Removal of calcium ions from aqueous solutions by sugar cane bagasse modified with carboxylic acids using microwave-assisted solvent-free synthesis. *Desalination*. 2011;278:18–25.
- [15] Dey S, Ganugula TNV, Padavala SB, Akula VPM. An experimental study on the parthenium biosorbents for removal of chlorides and hardness from contaminated water. *Energy Nexus*. 2024;15:100309.
- [16] Altundoğan HS, Topdemir A, Cakmak M, Bahar N. Hardness removal from waters by using citric acid modified pinecone. *J Taiwan Inst Chem Eng*. 2016;58:219–225.
- [17] Pawanna P. Environmental-friendly ion exchange resin from water hyacinth. *Life Sci Environ J*. 2023;24(2):443–455.
- [18] Tran ATK, Hoang NTT, Nguyen PT. Optimizing sulfonation process of polystyrene waste for hardness and heavy metal removal. *Case Stud Chem Environ Eng*. 2023;8:100396.
- [19] Chamkrom B. Bagasse resin for removal of dyes from dyeing wastewater [Master's thesis]. Khon Kaen: Khon Kaen University; 2003.
- [20] APHA. Standard methods for the examination of water and wastewater. 23rd ed. Washington (DC): American Public Health Association; 2017.
- [21] Chawakitchareon P, Sanguanduan N. Copper removal by ion exchange resin made from corn cob, soybean hull and sunflower stalks. In: *Proceedings of the 41st Kasetsart University Annual Conference*; 2003 Feb 3–7; Bangkok, Thailand. Bangkok: The Thailand Research Fund; 2003, p. 346–351.
- [22] Li R, Fei J, Cai Y, Li Y, Feng J, Yao J. Cellulose whiskers extracted from mulberry: A novel biomass production. *Carbohydr Polym*. 2009;76(1):94–99.
- [23] Md Salim R, Asik J, Sarjadi MS. Chemical functional groups of extractives, cellulose and lignin extracted from native *Leucaena leucocephala* bark. *Wood Sci Technol*. 2021;55:295–313.
- [24] Xia Y, Li X, Zhuang J, Wang W, Abbas SC, Fu C, et al. Exploitation of functional groups in cellulose materials for lithium-ion batteries applications. *Carbohydr Polym*. 2024;325:121570.
- [25] Roman M, Winter WT. Effect of sulfate groups from sulfuric acid hydrolysis on the thermal degradation behavior of bacterial cellulose. *Biomacromolecules*. 2004;5(5):1671–1677.

- [26] Barua VB, Kalamdhad AS. Effect of various types of thermal pretreatment techniques on the hydrolysis, compositional analysis and characterization of water hyacinth. *Bioresour Technol.* 2017;227:147–154.
- [27] DuPont. Ion exchange resins selectivity [Internet]. 2019 [cited 2025 Jan 5]. Available from: <https://www.dupont.com/content/dam/water/amer/us/en/water/public/documents/en/IER-Selectivity-TechFact-45-D01458-en.pdf>
- [28] Marin NM, Lazar NM, Popa M, Galaon T, Pascu LF. Current trends in development and use of polymeric ion-exchange resins in wastewater treatment. *Materials (Basel)*. 2024;17(23):5994.
- [29] Galizia M, Benedetti FM, Paul DR, Freeman BD. Monovalent and divalent ion sorption in a cation exchange membrane based on cross-linked poly(p-styrene sulfonate-co-divinylbenzene). *J Membr Sci.* 2017;535:132–142.
- [30] Tiwari U, Cummins E. Functional and physicochemical properties of legume fibers. In: Tiwari BK, Gowen A, McKenna B, editors. *Pulse foods*. Academic Press; 2011, p. 121–156.
- [31] Meesrisom S, Padungthon S. Regeneration efficiency of strong acid cation exchange resin using low concentration of NaCl from synthetic RO reject water. *KKU Res J (Grad Stud)*. 2023;23(4):13–26.
- [32] de Abreu Domingos R, da Fonseca FV. Evaluation of adsorbent and ion exchange resins for removal of organic matter from petroleum refinery wastewaters aiming to increase water reuse. *J Environ Manage.* 2018;214:362–369.
- [33] Zheng JC, Feng HM, Lam MHW, Lam PKS, Ding YW, Yu HQ. Removal of Cu(II) in aqueous media by biosorption using water hyacinth roots as a biosorbent material. *J Hazard Mater.* 2009;171:780–785.
- [34] Rosidah R, Rahayu SYS, Susanti E. Removal of cadmium (II) by adsorption using water hyacinth (*Eichhornia crassipes*) dried biomass. *J Ecol Eng.* 2023;24(3):246–253.
- [35] Boonpanaid C, Piyamongkala K. Using commercial resin for ion exchange to remove hardness from domestic water supply. *Mater Today Proc.* 2023.