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SYNTHESIS, CHARACTERIZATION, AND POTENTIAL USE OF A SULFONATED CATION-EXCHANGE RESIN FOR HARD-WATER SOFTENING

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ABSTRACT

This study synthesized and characterized a monofunctional sulfonic cation-exchange resin from sodium p-styrenesulfonate and furfural and evaluated its potential for hard-water softening. The effects of reactant ratio, reaction temperature, and zinc chloride catalyst loading were examined. The selected synthesis condition was a 1:1 molar ratio of sodium p-styrenesulfonate to furfural, 90 °C, and 0.07 mol $ZnCl_2$ per mole of furfural. Infrared spectroscopy and potentiometric titration supported assignment of strongly acidic $–SO_3H$ functionality, with an apparent pK_h of 1.8–2.2. The resin showed a static exchange capacity of 4.2–4.5 meq/g by 0.1 N NaOH titration, a total dynamic exchange capacity of 1,480 meq/L, an operating dynamic exchange capacity of 1,200 meq/L, and mechanical durability of 99.0%. Single-cycle desorption recovered approximately 90.5%–92.5% of sorbed Na^+, Ca^{2+}, and Mg^{2+}. In regional hard-water samples with initial hardness of 11.0–12.0 meq/L, treatment reduced hardness to 3.0–3.8 meq/L in the H-form and 2.1–2.4 meq/L in the Na-form. A tap-water sample decreased from 3.5 meq/L to 0.8 and 0.4 meq/L after 6 h with the H- and Na-forms, respectively. The results support further development of the material for water softening; however, discrepancies among exchange-capacity measurements, incomplete reporting of replicate statistics, and the absence of regeneration-cycle and scale-up data limit claims of superiority over commercial resins.

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Keywords: *cation-exchange resin, furfural, sodium p-styrenesulfonate, ion exchange, water softening, calcium, magnesium.*

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Introduction

Ion-exchange resins remain important in water treatment, hydrometallurgy, analytical separations, and process-water conditioning because fixed ionic groups can reversibly exchange counterions while the cross-linked polymer matrix remains insoluble. Their practical value depends on exchange capacity, selectivity, diffusion within the polymer phase, swelling, chemical stability, and regenerability (Alexandratos, 2009; Harland, 1994; Marin et al., 2024; Zagorodni, 2007). Ion exchange is also widely used for recovery or removal of metal ions and other ionic contaminants from aqueous streams (Dixit et al., 2021; Jorgensen & Weatherley, 2003; Lebron et al., 2021; Pehlivan & Altun, 2007).

For sulfonated styrenic materials, the balance between functional-group density and cross-linking is especially important. Cross-linking and pore morphology affect hydration, swelling, transport, and accessible exchange sites, while synthesis conditions influence bead or network structure and therefore macroscopic performance (Chaudhary & Sharma, 2019; Dalla Valle et al., 2020; Rahmatpour et al., 2018; Sterchele et al., 2014; Yuchi et al., 2010). Research on sulfonated styrene-divinylbenzene systems has further shown that sulfonation conditions, porosity, internal acid environment, and morphology influence acidity and ion-exchange behavior (Ahmed et al., 2004; Ali et al., 2012; Coutinho et al., 2006; Hart et al., 2002; Koujout et al., 2003; Malik et al., 2010; Oliveira et al., 2005; Pirogov et al., 2003; Zhou et al., 2010). Related styrenic mixed-mode materials continue to be developed through controlled functionalization of polymer surfaces and networks (Gorbovskaia et al., 2024).

Furfural provides a route to polycondensation materials that can incorporate a feedstock derived from pentosan-rich biomass. Furfural-based ion-exchange polymers and related polycondensation matrices have been investigated using aromatic monomers, industrial residues, and biomass-derived components, including work focused on locally available raw materials and wastewater treatment (Berdieva, 2016; Igitov et al., 2016; Makhmudov et al., 2021; Pulatov & Turabjanov, 2016; Rakhimova, 2016; Turabdzhanov et al., 2019; Usmonova & Pulatov, 2025; Yabefa et al., 2010). Such systems are of interest where the objective is to reduce dependence on imported ion-exchange materials while retaining adequate exchange capacity and mechanical integrity.

Water softening is a particularly relevant application because Ca^{2+} and Mg^{2+} cause scaling in domestic and industrial systems. Ion-exchange treatment can reduce these hardness ions, but engineering performance must be judged under both equilibrium and dynamic conditions and should include regeneration behavior and transport limitations (Crittenden et al., 2012; Nesbitt & Petersen, 2020). Strong-acid cation exchangers have also been investigated for Cu^{2+}, Zn^{2+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, and Cr^{3+} removal, illustrating the broader divalent-cation affinity expected from sulfonic-acid resins (Demirbas et al., 2005; Fathy et al., 2014; Fil et al., 2012; Gode & Pehlivan, 2006; Kocaoba, 2007; Lee et al., 2007).

The purpose of the present study was to synthesize a sulfonic cation-exchange resin by polycondensation of sodium p-styrenesulfonate with furfural, identify conditions associated with favorable exchange properties, characterize the acid functionality, compare selected ion-exchange properties with reference resins, and assess the material in hard-water softening. Particular attention was given to Ca^{2+} and Mg^{2+} removal because these ions directly determine water hardness.

Materials and Methods

Reporting Basis and Units

The numerical values in this manuscript are retained from the experimental record. Exchange capacity and water hardness were originally reported in “mg-eq” units; these values are expressed here as milliequivalents (meq) without changing the numerical values. No replicate counts, standard deviations, confidence intervals, or inferential statistical tests were reported. Accordingly, ranges are presented descriptively and are not interpreted as statistical uncertainty.

Resin Synthesis and Optimization

A three-necked flask fitted with a reflux condenser and mechanical stirrer was charged with 0.1 mol (21.2 g, as reported) of sodium p-styrenesulfonate and 0.1 mol (9.6 g) of furfural. The mixture was heated to 60–70 °C until the salt dissolved. Zinc chloride was then added as catalyst, and the reaction mixture was heated further. In the baseline preparation, gel formation was observed after approximately 2.5 h at 80–85 °C. The gel was transferred to a porcelain dish, dried at 90 °C for 24–30 h, ground, washed to remove low-molecular-weight products, and converted to the H-form before characterization.

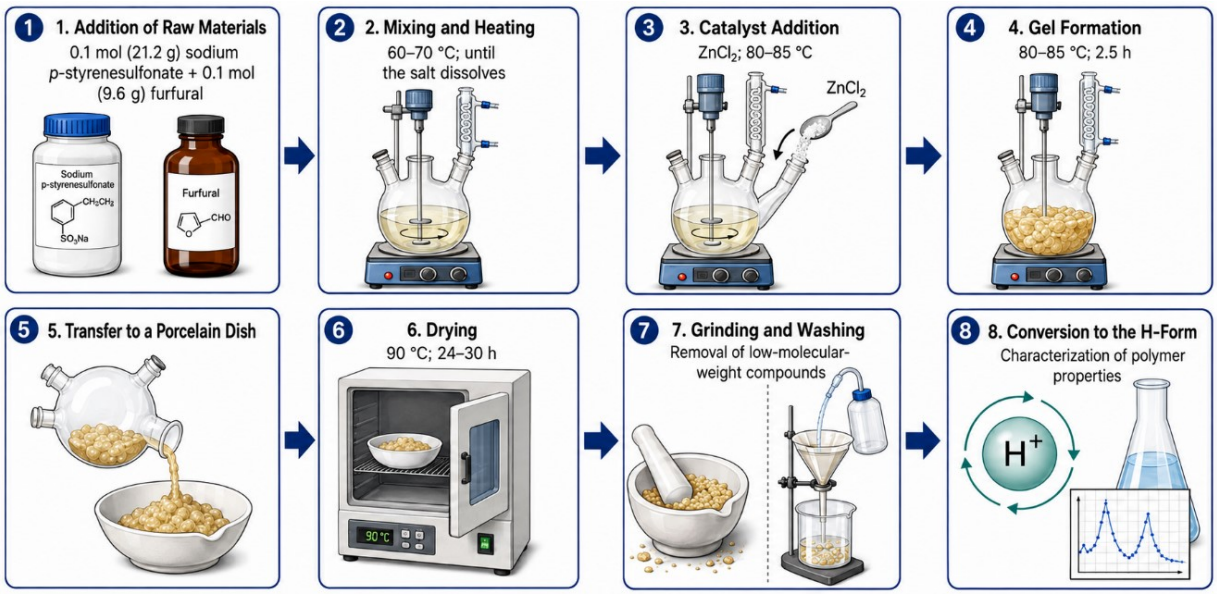
Optimization experiments evaluated reaction temperature at 80, 90, and 100 °C with a 1:1 reactant ratio and evaluated sodium p-styrenesulfonate-to-furfural molar ratios of 2:1, 1.5:1, and 1:1. The experimental record reports the selected $ZnCl_2$ loading as 0.07 mol per mole of furfural but does not provide

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the full set of catalyst concentrations tested. The selected overall condition was 90 °C, a 1:1 reactant ratio, and 0.07 mol $ZnCl_2$ per mole of furfural. The reaction was interpreted using conventional polycondensation concepts (Korshak & Vinogradova, 1968).

Figure 1

Laboratory Workflow for Synthesis and Conversion of the Resin to the H-Form



Note. The workflow reproduces the sequence reported in the experimental record: addition of sodium p-styrenesulfonate and furfural, dissolution, $ZnCl_2$ addition, gel formation, drying, grinding/washing, and H-form conversion.

Total Static Exchange Capacity

A resin sample equivalent to 1.0 g on a dry-matter basis was contacted with 100 mL of 0.1 N NaOH for 24 h. A 25 mL filtrate aliquot was then titrated with 0.1 N HCl in the presence of a mixed indicator. Static exchange capacity, E, was calculated as follows:

$$E = [(V \cdot K_1 - K \cdot V_1 \cdot K_2) \times 100 \times c] / [m \times (100 - W)]$$

where V is the volume of working solution (mL), K is the ratio of total working-solution volume to aliquot volume, V_1 is the titrant volume for the post-contact aliquot (mL), m is resin mass (g), W is moisture content by mass (%), c is the nominal normal concentration of the working and titrating solutions (0.1 N), and K_1 and K_2 are correction factors for the working and titrating solutions, respectively.

Dynamic Exchange Capacity

Resin prepared according to GOST 10896 was stored under distilled water, transferred to a 100 cm^3 graduated cylinder, compacted, and adjusted to a bed volume of 100 cm^3. The resin was transferred to a column and washed downward with distilled water at 1.0 dm^3/h until acidity was no longer detected with methyl orange. A 0.1 N working solution was then passed through the bed and filtrate was collected in measured portions. Breakthrough capacity was determined from the filtrate volume before working-solution ions appeared, and total dynamic capacity was determined when filtrate concentration matched the influent. The results section identifies 0.1 N NaOH as the working solution for the reported dynamic-capacity measurements.

$$D = (V_f \times c \times 1000) / V_s$$

where D is the dynamic exchange capacity (meq/L), Vf is the filtrate volume passed before breakthrough (cm^3), c is working-solution normality, and Vs is the resin-bed volume (cm^3).

Potentiometric Titration and Infrared Characterization

For potentiometric titration, 0.25 g portions of H-form resin were equilibrated for 48 h with decreasing volumes of 0.1 N NaCl and increasing volumes of 0.1 N NaOH while total liquid volume was maintained at 100 mL. Equilibrium pH was measured with a pH-150MI meter, and pH was plotted against added NaOH. The apparent dissociation constant was obtained from the titration curve according to the procedure used in the experimental record. Infrared spectroscopy was used to identify the principal functional groups; instrument model, sampling configuration, and acquisition parameters were not reported.

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Chemical Stability

Two H-form resin samples, each equivalent to 1.0 g dry resin, were separately treated with 100 mL of 5 N H_2SO_4 or 100 mL of 5 N NaOH under reflux in a boiling-water bath for 5 h. After cooling and filtration, the resin was reconverted to H-form and its exchange capacity and specific volume were determined. Chemical stability, X, was defined as the percentage of initial exchange capacity retained after treatment:

$X = (E_1 / E_0) \times 100$

where E_0 and E_1 are the total exchange capacities before and after acid or alkali treatment, respectively. Numerical E_0, E_1, and X values were not included in the available experimental record, so no quantitative stability comparison is reported in the Results.

Static Sorption-Rate Test

Ten Na-form resin samples, each equivalent to 0.25 g dry resin, were contacted with 50 mL of 0.1 N $CaCl_2$ in stoppered 150 mL flasks under shaking. At selected contact times, 10 mL aliquots were withdrawn and Ca^{2+} content was determined. The commercial KU-2×8 sulfonic cation-exchange resin was used for comparison. The experimental record states that kinetic curves were constructed, but the time-resolved data and curves were not available for quantitative kinetic modeling in this manuscript.

Desorption and Water-Softening Tests

For desorption, separate resin samples saturated with Na^+, Ca^{2+}, or Mg^{2+} were contacted with water and 2 N H_2SO_4; the acid-contact period was 48 h. For water-softening tests, 1.0 g of resin in either H- or Na-form was contacted with 200 mL of natural water for 24 h. Total hardness was measured by complexometric titration with Trilon B (EDTA) using Eriochrome Black T. Samples were obtained from Shurchi District in Surkhandarya Region and from Kungrad and Karaozak districts in the Republic of Karakalpakstan. A separate deep-softening test used tap water with an initial hardness of 3.5 meq/L and a 6 h contact period.

Results

Optimization and Physicochemical Properties

The 1:1 sodium p-styrenesulfonate-to-furfural ratio produced the highest NaOH-based static exchange capacity among the three ratios reported and also gave the largest swollen specific volume. At this ratio, moisture content was 26%, bulk density was 0.56 g/mL, swollen H-form specific volume was 2.8–3.0 mL/g, and static exchange capacities were 4.2–4.5 meq/g with NaOH, 3.0–3.2 meq/g with NaCl, and 4.0–4.2 meq/g with $CaCl_2$. Together with the temperature and catalyst studies, the selected synthesis condition was 90 °C, 0.07 mol $ZnCl_2$ per mole of furfural, and a 1:1 reactant ratio.

Table 1

Physicochemical Characteristics as a Function of Sodium p-Styrenesulfonate-to-Furfural Molar Ratio

Parameter	Unit	2:1	1.5:1	1:1
Moisture content	%	28	26	26
Bulk density	g/mL	0.68	0.60	0.56
Swollen H-form specific volume	mL/g	2.4–2.8	2.6–2.8	2.8–3.0
Static exchange capacity by 0.1 N NaOH	meq/g	2.9–3.0	3.6–3.8	4.2–4.5
Static exchange capacity by 0.1 N NaCl	meq/g	2.4–2.6	2.8–3.0	3.0–3.2
Static exchange capacity by 0.1 N $CaCl_2$	meq/g	3.6–3.8	3.6–3.8	4.0–4.2

Note. The original manuscript reported exchange capacity as mg-eq/g; the numerical values are shown here as meq/g. No replicate counts or measures of dispersion were provided.

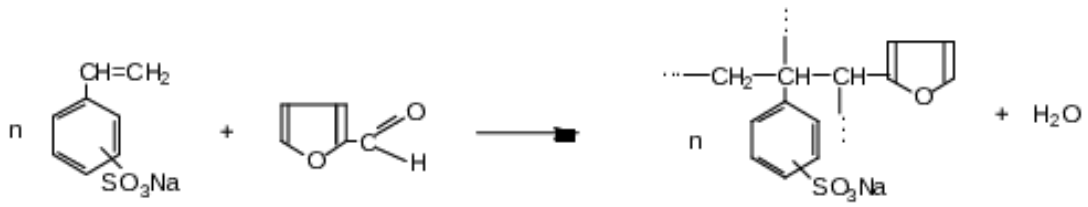
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Proposed Reaction and Functional-Group Characterization

The reported reaction scheme treats furfural as both a condensation component and a contributor to network formation. The proposed structure is shown in Figure 2. The infrared spectrum was interpreted as evidence for sulfonic-acid functionality: bands in the 1260–1150 cm^{-1} and 1060–1010 cm^{-1} regions were assigned to $–SO_3H$ groups, with a prominent feature near 1200 cm^{-1}. The experimental record reports no diagnostic hydroxyl or carboxyl bands in the corresponding regions used for assignment and therefore classifies the material as monofunctional.

Figure 2

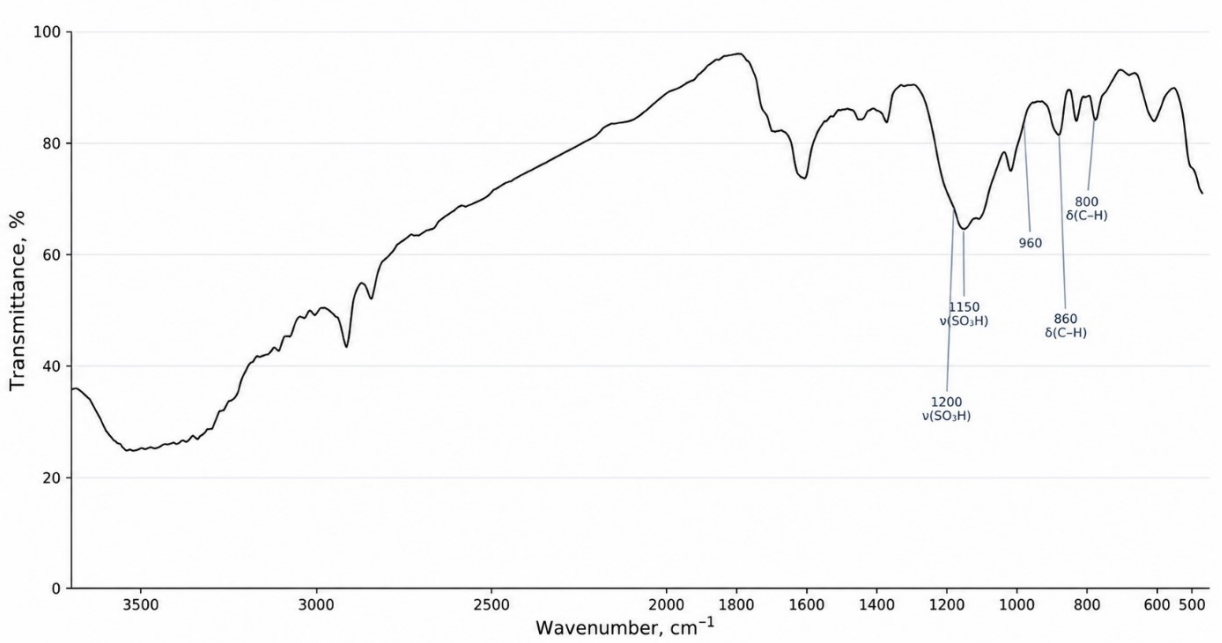
Proposed Polycondensation Scheme for Sodium p-Styrenesulfonate and Furfural



Note. The scheme is reproduced from the experimental record and is presented as a proposed structural representation rather than a complete mechanistic proof.

Figure 3

Infrared Spectrum of the Synthesized Sulfonic Cation-Exchange Resin



Note. Bands annotated near 1,200 and 1,150 cm^{-1} were assigned in the experimental record to sulfonic-acid vibrations; features near 960, 860, and 800 cm^{-1} were assigned to aromatic C–H deformation modes.

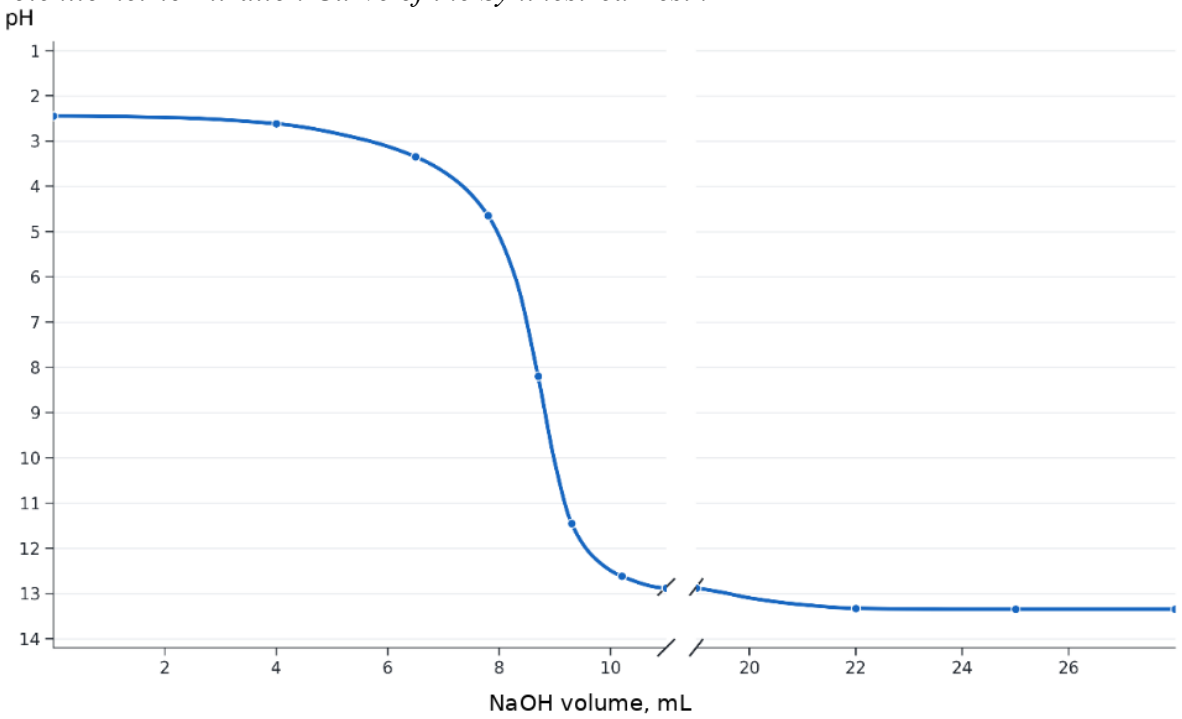
Potentiometric Behavior and Cross-Method Exchange Capacity

The potentiometric titration yielded an apparent pK_h of 1.8–2.2, consistent with the strongly acidic behavior attributed to sulfonic-acid groups. The reported capacity estimates, however, were not fully concordant. For the synthesized resin, theoretical and sulfur-based capacities were both 3.6 meq/g, potentiometric capacity was 3.2–3.4 meq/g, whereas the NaOH static capacity was 4.2–4.5 meq/g. Thus, the NaOH value exceeded the stated theoretical capacity by approximately 17%–25%. Without replicate statistics or a mass-balance explanation, the difference should be treated as a reporting or method-comparability limitation rather than as evidence of additional exchange sites.

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Figure 4

Potentiometric Titration Curve of the Synthesized Resin



Note. The vertical pH axis is inverted in the original experimental figure (lower pH values appear at the top). The apparent pK_h reported from the curve was 1.8–2.2.

Table 2

Exchange-Capacity Estimates and Apparent Dissociation Constants

Characteristic	KU-FS resin	Synthesized resin	Unit
Functional group	–SO_3H	–SO_3H	—
Theoretical exchange capacity	3.8	3.6	meq/g
Static exchange capacity by 0.1 N NaOH	3.4–3.6	4.2–4.5	meq/g
Capacity calculated from S/P content	3.53	3.6	meq/g
Capacity from potentiometric titration	3.4–3.5	3.2–3.4	meq/g
Apparent pK_1	1.8–2.2	1.8–2.2	—
pK_2	—	—	—

Note. KU-FS denotes the comparison sulfonic cation-exchange resin based on a styrene–furfural polymer. The source table labels the elemental-analysis column as sulfur (phosphorus) content; the present sulfonic resins are interpreted on the sulfur basis.

Comparative Ion-Exchange Properties

The synthesized resin displayed 99.0% mechanical durability, equal to the KU-FS value and slightly below the 99.9% reported for KU-2×8. Its Ca^{2+} exchange capacity approached that of KU-2×8, whereas Mg^{2+} and Cu^{2+} capacities were lower than the corresponding KU-2×8 values. Ni^{2+} data were available for the synthesized resin and KU-FS but not for KU-2×8. These comparisons indicate useful

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divalent-cation exchange but do not support a general claim of superior sorption relative to the commercial resin.

Table 3

Comparative Properties of the Synthesized Resin and Reference Cation-Exchange Resins

Property	Synthesized resin	KU-FS	KU-2×8
Bulk density, g/mL	0.68	0.50	0.45
Specific volume, mL/g	2.4–2.8	3.4	2.8
NaOH static capacity, meq/g	4.2–4.5	3.6	3.8
NaCl static capacity, meq/g	3.0–3.2	3.4	1.2
$CaCl_2$ capacity, H-form, meq/g	4.0–4.2	4.4	4.6
$CaCl_2$ capacity, Na-form, meq/g	4.4–4.6	4.6	5.4
$MgCl_2$ capacity, H-form, meq/g	2.6–3.0	3.0	4.0
$MgCl_2$ capacity, Na-form, meq/g	2.8–3.4	3.4	4.6
$CuSO_4$ capacity, H-form, meq/g	2.0–2.2	3.8	4.0
$CuSO_4$ capacity, Na-form, meq/g	2.4–2.6	4.2	4.6
$NiSO_4$ capacity, H-form, meq/g	1.8–2.0	2.0	—
$NiSO_4$ capacity, Na-form, meq/g	2.2–2.4	3.6	—
Mechanical durability, %	99.0	99.0	99.9

Note. The bulk-density and specific-volume values reported for the synthesized resin in this comparison differ from the values reported for the selected 1:1 sample in Table 1. The experimental record does not identify whether the measurements represent a different batch, resin form, or reporting basis; therefore, both sets are retained without silent alteration.

Dynamic Capacity and Desorption

Under dynamic conditions with 0.1 N NaOH, the synthesized resin had a total capacity of 1,480 meq/L and an operating capacity of 1,200 meq/L, compared with 1,420 and 1,150 meq/L for KU-FS. These differences correspond to approximately 4.2% and 4.3%, respectively. Single-cycle desorption recovered 90.5% of sorbed Na^+, 92.5% of Ca^{2+}, and 92.3% of Mg^{2+} when the water and 2 N H_2SO_4 fractions were combined.

Table 4

Static, Swelling, and Dynamic Exchange Properties

Characteristic	KU-FS	Synthesized resin
Static capacity by 0.1 N NaOH, meq/g	3.6	4.2–4.5

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Characteristic	KU-FS	Synthesized resin
Static capacity by 0.1 N NaCl, meq/g	3.4	3.0–3.2
Specific volume, H-form, mL/g	3.5	2.4
Specific volume, Na-form, mL/g	3.8	2.8
Total dynamic capacity, meq/L	1,420	1,480
Operating dynamic capacity, meq/L	1,150	1,200

Note. Specific-volume values in this source table differ from the 1:1 optimization values in Table 1. No batch or resin-form explanation was provided beyond the H-form/Na-form labels shown here.

Table 5

Desorption of Sorbed Ions

Cation	Sorbed, meq/g	Desorbed with H_2O, meq/g	Desorbed with 2 N H_2SO_4, meq/g	Total desorbed, meq/g
Na^+	4.2	0.3	3.5	3.8
Ca^{2+}	4.0	0.1	3.6	3.7
Mg^{2+}	2.6	0.1	2.3	2.4

Note. Calculated total desorption recoveries are approximately 90.5% for Na^+, 92.5% for Ca^{2+}, and 92.3% for Mg^{2+}. The record describes a single desorption experiment; repeated regeneration cycles were not reported.

Hard-Water Softening

The resin reduced hardness in all three regional water samples. In the H-form, hardness decreased from 11.0–12.0 meq/L to 3.0–3.8 meq/L, equivalent to reductions of approximately 68.3%–73.2%. In the Na-form, final hardness was lower, 2.1–2.4 meq/L; using the same initial sample values reported for the H-form rows, the corresponding reductions were approximately 78.2%–82.5%. The H-form results fell within the 2.5–7.0 meq/L range cited in the experimental record for O‘zDSt 950:2011, while the Na-form produced still softer water (O‘zDSt 950:2011, 2011).

Table 6

Water Hardness Before and After Treatment With the Synthesized Resin

Sampling location	Initial hardness, meq/L	Final hardness, H-form, meq/L	Final hardness, Na-form, meq/L
Shurchi District, Surkhandarya Region	12.0	3.8	2.1
Kungrad District, Republic of Karakalpakstan	11.2	3.0	2.2
Karaozak District, Republic of Karakalpakstan	11.0	3.4	2.4

Note. The source table printed initial hardness only once for each water source and used dashes in the Na-form initial-hardness cells. The present layout treats each initial value as the common starting hardness for the corresponding water source before separate H-form and Na-form tests.

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In the separate deep-softening test, tap water with an initial hardness of 3.5 meq/L decreased to 0.8 meq/L with the H-form and 0.4 meq/L with the Na-form after 6 h, corresponding to reductions of approximately 77.1% and 88.6%, respectively. These values demonstrate strong hardness removal under the reported batch conditions, although they should not be generalized to continuous operation without column breakthrough and regeneration-cycle data.

Discussion

The optimization data indicate that increasing the relative amount of furfural from the 2:1 to the 1:1 sodium p-styrenesulfonate-to-furfural ratio was associated with higher NaOH-based exchange capacity and greater swelling. This pattern is qualitatively consistent with the broader literature showing that synthesis conditions and network morphology can strongly affect the accessibility and hydration of ion-exchange sites (Chaudhary & Sharma, 2019; Dalla Valle et al., 2020; Rahmatpour et al., 2018; Sterchele et al., 2014). At the same time, excessive cross-linking can reduce diffusion and swelling, so the observed optimum should be understood as specific to the reported formulation and test conditions rather than a universal stoichiometric rule.

The IR and potentiometric data support classification of the resin as a strong-acid sulfonic cation exchanger. This interpretation is consistent with established behavior of sulfonated styrenic networks, in which $–SO_3H$ functionality provides strongly acidic exchange sites over a broad pH range (Hart et al., 2002; Koujout et al., 2003; Malik et al., 2010). However, the cross-method capacity comparison reveals an important internal inconsistency: the 4.2–4.5 meq/g NaOH value is higher than the stated theoretical and sulfur-based capacities of 3.6 meq/g. Because a measured exchange capacity should be interpreted against the same dry-mass and chemical-equivalent basis as the theoretical value, this discrepancy requires confirmation through replicated titrations, independent sulfur analysis, and explicit moisture corrections before the higher value is used for design calculations.

Performance comparisons were mixed rather than uniformly favorable. The synthesized resin slightly exceeded KU-FS in total and operating dynamic capacity, but KU-2×8 showed higher Ca^{2+}, Mg^{2+}, and Cu^{2+} capacity in most directly comparable tests. The synthesized material therefore appears promising as a functional ion exchanger but cannot be described as generally superior to the commercial reference based on the reported dataset. Similar caution is appropriate for heavy-metal applications: sulfonic resins are well established for divalent-ion exchange (Demirbas et al., 2005; Fil et al., 2012; Gode & Pehlivan, 2006; Kocaoba, 2007; Lee et al., 2007), yet metal-specific selectivity, competing-ion effects, and column performance would need to be measured for this material.

The hard-water experiments provide the clearest application evidence. Both resin forms substantially reduced hardness, and the Na-form consistently produced lower final hardness than the H-form in the three regional samples and the tap-water test. This is consistent with the practical use of Na-cycle strong-acid cation exchangers for softening because Ca^{2+} and Mg^{2+} are exchanged for Na^{+} without acidifying the product water to the same extent as an H-cycle resin. The reported single-cycle desorption of more than 90% for Na^{+}, Ca^{2+}, and Mg^{2+} is also encouraging, but repeated exhaustion-regeneration cycles are necessary to establish working capacity, resin life, and regenerant demand under realistic conditions (Crittenden et al., 2012).

Limitations

Several limitations constrain interpretation. First, replicate numbers and statistical uncertainty were not reported, so numerical ranges cannot be treated as confidence intervals. Second, the full catalyst-loading series, IR instrument conditions, and time-resolved kinetic data were not available. Third, quantitative chemical-stability results were absent even though a stability method was described. Fourth, bulk-density and specific-volume values differ across the reported tables without batch identifiers, and the NaOH exchange capacity exceeds the stated theoretical capacity. Fifth, the water-softening tests were batch experiments using a high resin-to-water ratio (1 g per 200 mL) and did not include continuous breakthrough

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curves, multi-cycle regeneration, long-term mechanical attrition, cost analysis, or comparison with modern commercial resins under identical conditions. These issues should be addressed before scale-up or economic claims are made.

Conclusion

A sulfonic cation-exchange resin was synthesized from sodium p-styrenesulfonate and furfural, with the most favorable reported condition at a 1:1 reactant ratio, 90 °C, and 0.07 mol $ZnCl_2$ per mole of furfural. IR and potentiometric results were consistent with strongly acidic $–SO_3H$ functionality, and the resin showed measurable static and dynamic exchange capacity, 99.0% mechanical durability, more than 90% single-cycle desorption of Na^+, Ca^{2+}, and Mg^{2+}, and substantial reduction of hardness in regional and tap-water samples. The Na-form produced the lowest residual hardness. The material is therefore a credible candidate for further water-softening development, but the present evidence supports a “promising” rather than “superior” conclusion. Replicated capacity measurements, reconciliation of table-to-table data differences, full chemical-stability reporting, continuous-flow tests, regeneration cycling, and cost analysis are required for rigorous comparison with commercial cation-exchange resins.

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