Sustainable K\(^+\)/Na\(^+\) monovalent-selective membranes with hot-pressed PSS-PVA saloplastics

Ameya Krishna B\(^{a,b,d}\), Harmen J. Zwijnenberg\(^{b,c}\), Saskia Lindhoud\(^{d,*}\), Wiebe M. de Vos\(^{a}\)

\(^{a}\) Membrane Surface Science, Membrane Science and Technology, MESA+ Institute of Nanotechnology, University of Twente, Enschede, the Netherlands
\(^{b}\) European Membrane Institute (EMI), Twente, the Netherlands
\(^{c}\) Membrane Technology and Engineering for Water Treatment (MTEWT), University of Twente, Enschede, the Netherlands
\(^{d}\) Department of Molecules and Materials, MESA+ Institute of Nanotechnology, University of Twente, Enschede, the Netherlands

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**ABSTRACT**

Monovalent selective cation exchange membranes could play an important role in balancing the K\(^+\)/Na\(^+\) ratio in agricultural feed streams to prevent the toxic effects of excess Na\(^+\) in the plant and soil systems, especially in greenhouses and dry areas. A polyelectrolyte complex of polystyrenesulfonate and polyvinylamine in the monomer ratio 1:2.5 is hot-pressed to form a dense saloplastic. The plastic takes up 42% w/w water when equilibrated, while ion-exchange capacity measurements show that it is negatively charged with a net ion-exchange capacity of 1.1 ± 0.4. Resistance measurements show a very promising preferred conductivity for K\(^+\) over Na\(^+\). This was confirmed by measuring K\(^+\) and Na\(^+\) transport through the membrane under diffusive conditions from an aqueous mixture of KCl and NaCl. Commercial membranes show resistance-based selectivities of 1.32 ± 0.1 to 1.19 ± 0.1, and diffusion based selectivities of 0.99 ± 0.1 to 0.78 ± 0.1. In contrast, the selectivities for the newly developed saloplastic membrane were 1.80 ± 0.33 for the resistance-based selectivity while the diffusion-based selectivity was 1.91 ± 0.1. The procedure is green as toxic solvents and/or halogenating agents, typically used to make cation exchange membranes, are not needed. This work thus highlights how monovalent selective membranes with a relevant K\(^+\)/Na\(^+\) selectivity can be prepared by a simple and sustainable hot-pressing approach.

1. Introduction

Salts are imperative to the growth and development of living beings. The demand of each salt ion, such as Na\(^+\), Ca\(^{2+}\), K\(^+\), Cl\(^-\), I\(^-\), and PO\(_4^{3-}\), is in a specific range. Optimal quantities and relative ratios are important for an organism as they help regulate the osmolarity and pH of organs, tissues, and cells. In humans, the body utilizes salt ion buffers to maintain homeostasis of the blood pH at 7.4 [1]. Also, the electrical activity of neurons, enzymatic digestion, biochemical reactions, the osmolarity of tissues, and cells, etc depend on the balance of salt ions in specific pH ranges. An excessive intake of sodium, for example, can lead to hypertension and reduced bone density, and in extreme cases to cardiovascular diseases and carcinoma [2].

This has also been observed in plants [3]. Plant growth and survival depend on the metabolic processes occurring in plant cells, which in turn are dependent on the balance of specific salt ions [4,5]. Imbalances induce abiotic stresses [6] leading to survival responses such as reduced photosynthesis and osmolyte accumulation, while in extreme cases, stomata closure and programmed cell death [7,8]. Collectively, they are accountable for the reduction of agricultural produce and loss of cultivable land, resulting in negative economic impacts [9]. Soil salinity induced abiotic stresses severely reduce the yield of crops that play a critical role in the worldwide food demand, namely rice and wheat, which account for over 28% of all crop area [10,11], and other important crops like corn and potatoes [12,13].

A majority of salt-imbalanced soils are known to have toxic Na\(^+\) concentrations [14]. Among salt imbalances, a high level of Na\(^+\) is known to cause ionic toxicity, oxidative stress, and the production of Reactive Oxygen Species (ROS) which damage the DNA [15]. Studies also show damages to the chloroplast which reduces the chlorophyll \(a\) and \(b\) quantities and impacts photosynthesis [16]. The plasma membrane loses its semipermeability due to the exchange of intracellular ion

* Corresponding author. Department of Molecules and Materials University of Twente, Faculty of Science and Technology, P.O. Box 217, 7500 AE, Enschede, the Netherlands.

E-mail address: s.lindhoud@utwente.nl (S. Lindhoud).

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and Na. A. Krishna B et al. reported high selectivities for ion combinations such as K and Ca in the plant [18].

The macronutrient K facilitates the flow of carbohydrates, nutrients, and water within plant tissues, functioning of stomata, and inhibit crop diseases. It activates enzymes making way for the production of starch, protein, and adenosine triphosphate (ATP) to optimise the rate of photosynthesis [19]. The K to Na ratios are studied as an indicator of healthy K concentration in plant tissues [20,21].

Additionally, water that is used for irrigation purposes in dry areas accumulates excess Na due to factors including evaporation, rainfall, and preferential uptake of K [22,23]. Several studies show that greenhouses also accumulate Na [24,25], and such an ion imbalance increases over time reducing soil quality, plant nutrition, and water uptake [26,27]. Further, Na build-up in the wastewater of greenhouses is known to be a predominant drawback in achieving minimal liquid discharge (MLD) aimed to maximise the reuse agricultural water and minimize disposal [28].

There are several methods to mitigate this partially or wholly. Soils oversaturated with Na may be flushed with low-salinity water [29]. Salts mixtures low in NaCl, including K+, Mg2+, and Ca2+ can be sprayed [30]. Fertilizing with Ca2+ has shown contradictory results in various studies. However, assisting K in its competition with Na for being absorbed by the roots in the soil has proven to be a sustainable method.

It is therefore desirable that the water has a greater K to Na ratio. This eventually balances the absorption, uptake, translocation, and distribution in the plant [21,31]. Ion exchange membranes are used to separate or remove specific ions from a solution mixture. However, K+ and Na+ have similar ion exchange equilibrium coefficients and physicochemical properties, and hence it is conventionally difficult to separate them [32]. Commercial membranes are not available for this application, and the few studies that have described such monovalent-monovalent ion selectivity are based on simulations [51,52] or preliminary studies [24,31,33,34]. Supported Liquid Membranes [53,54] and bilayered ion-exchange membranes [55] have also been used to correlate electrophoretic mobility, transport properties, and permeation rates. Such studies have given valuable insights into the behaviour of these ions and possibilities to separate them. Unfortunately, these membranes are expensive to make, may have complex operating procedures, or necessitate the use of extreme operating conditions in terms of pH, temperature, or pressure. In treating large streams even a modest selectivity between the ions can matter considerably.

While the use of polyelectrolytes and their complexes in various forms is not new to the membrane society, their application as free-standing films is still in its formative stages [35]. Especially, ion exchange and selectivity require charge and a certain density to achieve, let alone monovalent-monovalent selectivity. Bruening’s group has reported high selectivities for ion combinations such as K+/Mg2+, Li+/Co2+, and K+/La3+ by effectively coating PSS/PAH multilayers on Nafion membranes [36-38]. Saloplastic are novel materials made by salt-processing polyelectrolyte complexes [39] and have only very recently been used as anion exchange membranes [40]. The current work showcases a monovalent-monovalent K+/Na+ cation-selective membrane fabricated by processing a polyelectrolyte complex by a simple hot-pressing approach. The novel membrane is thoroughly characterized and its resistance and diffusion based selectivity for K+/Na+ is compared to that of commercially available membranes.

2. Materials and methods

2.1. Materials

Poly(sodium 4-styrene sulfonate) (Na-PSS, Mw = 1000 kg mol-1, 25 wt% in H2O), KBr (>99%), NaCl (>99%), and K2CrO4 (>99%), 0.1 M AgNO3 solution, and K2CrO4 (>99%) were obtained from Merck Nederland. Polyvinylamine hydrochloride (PVA-HCl) purchased as Xelorex RS1300 (MW = 350 kg mol−1) and used as received. Hydrochloric acid (HCl) as ACS reagent 37% and Sodium Hydroxide pellets was purchased from Merck, The Netherlands. Milli-Q water from a Millipore Synergy® Water Purification System was used to make polyelectrolyte solutions.

2.2. Polyelectrolyte complexation

Individual solutions of Na-PSS and PVA-HCl were prepared. To make each solution, KBr salt was first added to 100 mM (millimol) and dissolved, and then the polyelectrolyte was added to 125 mM. The solutions were then stirred for 15 min. Next, they were poured simultaneously in the ratio 1:2.5 according to their monomer repeat units respectively, into a third beaker. This was magnetically stirred to facilitate complexation.

After ~30 min of stirring, the complex was allowed to sit for 3 h. Further, excess water was removed by centrifuging the complex at 6000 rpm for 10 min to be able to handle it for processing.

2.3. Hot-pressing

An FVR20R Rollie Driptech Rosin Press was purchased from FVR, Canada. The aluminium plates of the hot-press were used to compress lab-designed moulds to hold the precipitate. A mould was made with rectangular Delrin® (DuPont) plates of dimensions 12 × 17 cm2. On the lower plate, a spacer made with PTFE coated Fiberglass (Lubriglas®-CHAP-1540) was glued and channels were created to allow excess polymer to escape, as described in a previous work [40]. The precipitate was weighed and placed in the centre of the mould, which was in turn placed between the aluminium plates of the hot-press. The temperature was set to 85 °C and allowed to heat from room temperature while the plates of the hot press only touched the mould without pressurising it. 10 min after the system reached 85 °C, a pressure of 150 bar was applied gradually so the plasticized polymer evenly distributes over the volume of the mould. In 15 min, the heating is switched off while the system is kept under pressure until the system cools to room temperature. The saloplastic is then retrieved from the mould.

2.4. Pre-treatment

The hot-pressed plastic was washed thoroughly in DI water to remove salt ions and equilibrated in the relevant test solution for 24 h prior testing (0.5 M KCl solution for the resistance measurements, and a solution containing 0.3 M each of NaCl and KCl for the concentration experiment).

2.5. Electrical resistance

The electrical resistance was measured similar to other different works [40-42] using a six-compartment cell. The KCl or NaCl solutions were maintained at a constant temperature of 25 ± 0.2 °C while platinum coated titanium electrodes applied currents. Calomel reference electrodes measured the potential drop across the membrane via narrow salt bridges (Fig. 1). Each obtained value was corrected for liquid resistance by subtracting a blank resistance measured in the absence of a membrane.

2.6. Selectivity by resistance in single cation system

The ion selectivity of the PSS-PVA membrane based on resistance measurements is given by the following equation:

Selectivity\text{K}\text{+} = \frac{R_{Na\text{+}}}{R_{K\text{+}}}.
Where $R_{Na^+}$ is that measured in NaCl and $R_{K^+}$ is the resistance measured in KCl solutions. Both solutions were made at the same ionic strengths for correct comparison.

### 2.7. Selectivity in a mixed cation system

The test membrane was placed between two chambers of circulating fluids (Fig. 2). One contained an aqueous solution of a mixture of NaCl and KCl (0.2 M each), while the other contained MilliQ water. Small samples were extracted from both the reservoirs at specific time intervals. In this case the selectivity is measured by the following equation:

$$\text{Selectivity}_{Na^+}^{K^+} = \frac{c_{K^+}}{c_{Na^+}}$$

Where $c_{K^+}$ and $c_{Na^+}$ are the concentrations of K$^+$ and Na$^+$ ions measured in samples taken at different time intervals.

### 2.8. Long-term stability of selectivity

The monovalent selectivity measurement in a mixed cation system was continuously allowed to run for 80 h.

### 2.9. Ion chromatography

A Metrohm® Eco IC analyzer was used to determine the concentrations of ions. The anionic eluent was 5 mM Na$_2$CO$_3$ with 0.2 mM NaHCO$_3$, and the cationic eluent was 4 mM HNO$_3$. Also, the anion and cation columns were Metrosep A Supp 17–150/4.0 and Metrosep C6 150/4.0, both purchased from Metrohm.

### 2.10. Ion-exchange capacity

Potentiometric titrations were performed to determine the anion and cation exchange capacities, AEC and CEC, of the films respectively [43]. To determine the IEC for the anions, the samples were first brought to the Cl$^-$ form. Next, the Cl$^-$ ions were replaced by SO$_4^{2-}$ ions. The number of chloride ions released was determined by titration with AgNO$_3$. About 0.2 g of the dry membrane was accurately weighted and soaked in 150 mL of 1.0 M NaCl for 24 h. Next, it was rinsed and soaked in MilliQ water for 90 min, during which the water was replaced several times to remove the sorbed NaCl. Finally, the film was soaked in 50 mL of 1.0 M Na$_2$SO$_4$, during which the solution was replaced twice to ensure a complete exchange of Cl$^-$ with SO$_4^{2-}$. These three solutions were

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Fig. 1. Measurement of the resistance to cation passage through the PSS-PVA CEM by circulating 0.5 M NaCl or KCl in the central chambers around the membrane.

Fig. 2. Monovalent-ion selectivity experiment by circulating an equimolar mixture of NaCl and KCl in one chamber and MilliQ water in the other. The water shell is rigid for Na$^+$ and fluid for K$^+$. The PSS-PVA cation exchange membrane is in between.
combined and titrated with 0.1 M AgNO₃ in the presence of the indicator K₂CrO₄. The endpoint was indicated by a red precipitate. The IEC was calculated as follows:

\[ \text{IonExchangeCapacity(IEC)} \left( \frac{\text{mmol}}{g} \right) = \frac{V_{\text{AgNO}_3}}{W_{\text{dry}}} \times C_{\text{AgNO}_3} \]

\[ V_{\text{AgNO}_3} \text{ and } C_{\text{AgNO}_3} \text{ are the volume and concentration of AgNO}_3 \text{ respectively.} \]

To determine the IEC for the cations, the sample was brought to the H⁺ form. 0.2 g of dry membrane was soaked in 150 mL of 0.5 M HCl for 24 h. Next, it was rinsed in MilliQ water and soaked for 2 h during which the water was replaced several times to remove sorbed HCl. Finally, the film was soaked in 50 mL of 1 M NaCl, and the solution was replaced twice to ensure complete exchange of H⁺ ions with Na⁺. These solutions were combined and titrated with 0.1 M NaOH, in the presence of a pH electrode (Metrohm pH 491). The IEC was calculated by the following equation:

\[ \text{CationExchangeCapacity} \left( \frac{\text{mmol}}{g} \right) = \frac{V_{\text{NaOH}}}{W_{\text{dry}}} \times C_{\text{NaOH}} \]

\[ V_{\text{NaOH}} \text{ and } C_{\text{NaOH}} \text{ are the volume and concentration of NaOH respectively.} \]

### 2.11 Water permeability

A dead-end filtration setup was used to measure the water permeability of the hydrated membranes for >60 h. Firstly, circles of diameter 25 mm were punched out of a hot-pressed membrane sheet. They were equilibrated for at least 24 h in an aqueous solution containing 0.3 M NaCl + 0.3 M KCl. Both feed and permeate side were filled with the same solution to ensure no osmotic pressure difference existed and a fast response to volume changes at the permeate side was obtained. As the membranes are used in an aqueous environment, the water permeability was also measured at 2.5 bar in 0.3 M NaCl + 0.3 M KCl aqueous solution. The permeate side was closed to minimize evaporation.

### 3. Results and discussion

A precipitated polyelectrolyte complex of PSS-PVA was pressed into a plastic film by hot-pressing. A key strength of this approach is that no organic solvents are required in the production process, making it sustainable compared to typical solvent casting based methods to prepare ion-exchange membranes. The plastic was transparent as seen in Fig. 3 a, and a field emission scanning electron microscope (lowest resolution 1.2 nm) image of the top surface is shown in Fig. 3 b. This showed that no pores or defects were present even at a resolution >100,000×. To further confirm the lack of pores, continuous water permeability measurement for >60 h was performed. The flux was observed to be below 0.2 mL/m²/h, being the detection limit of the instrument. Longer measurements most likely would have decreased the detection limit but lacked relevance as it results in a convective flux being less than 5.4 × 10⁻¹¹ m/s. The water uptake of these plastic films was measured to be 42 ± 6% when equilibrated in MilliQ water. A net negative charge of the membrane was observed by ion exchange capacity measurements, with a measured IEC value of 1.1 ± 0.4. Hence, the potential to be used as a cation exchange membrane was considered.

The ease with which a specific ion passes through a membrane material can be determined by measuring the ionic resistance (Fig. 1). Such determinations can also be used for comparative studies between two ions, wherein the membrane shows a higher transport resistance for one ion compared to another. A larger value suggests the need for a larger applied voltage, the driver, to facilitate ion transport. Resistance comparisons are known to be predictive for a selectivity [44], wherein the transport selectivity is the ratio of the resistances. Rijnaarts et al. reported such selectivity for monovalent-divalent ion pair Na⁺ and Mg²⁺ to be up to 7.8 [45].

Hot-pressed PSS-PVA membranes of 100 μm had a resistance of 6.2 ± 0.6 Ω cm² to K⁺ and 11.2 ± 0.8 Ω cm² to Na⁺ in 0.5 M aqueous KCl and NaCl solutions and are already corrected for changes in liquid conductivity (Fig. S12-3). The selectivity thus obtained is 1.80 ± 0.33. Such measurements were performed for membranes of three other thicknesses (70 μm, 150 μm, and 200 μm). Similar results were obtained and are reported in Fig. 4, but the best selectivity was found for thin membranes. Separating a mixture of monovalent-divalent ions is challenging, and even more so for two monovalent ions. Sodium and potassium cations are similar in many ways, including their physiochemical and electrochemical behaviour. Commonly used commercial cation exchange membranes Neosepta CMX and Sel顿ion AMV were tested under similar conditions for comparison, which showed selectivities of 1.32 ± 0.16 1/cm² and 1.19 ± 0.10 Ω cm² respectively.

Comparing the resistances offered to the passage of both ions is established through resistance-based selectivity by a straightforward measurement of voltage generated across the membrane while passing current. However, the complex interplay of factors finally resulting in a selectivity based on the measurement of ion concentrations is possible by the diffusion-based selectivity. While resistance based selectivity is an established method, measurement of ion fluxes strongly helps to confirm this effect. To achieve this, a membrane of 100 μm was placed in between two chambers, one with MilliQ water, and the other with a mixture of KCl and NaCl, 0.2 M each. Both solutions were circulated continuously to avoid stagnation of the liquid at the membrane surfaces (Fig. 2). Samples were taken from the reservoirs at different time intervals to determine the concentrations of Na⁺ and K⁺ ions by Ion Chromatography (Fig. 5a). The ratio of the normalised concentrations of K⁺ Nutrition and Na⁺ in the chamber initially containing MilliQ water is the

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**Fig. 3.** Hot-pressed PSS-PVA membranes showing (a) transparency and (b) micro structure.

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**Fig. 4.** The left axis shows the resistance to K⁺ (Δ) and Na⁺ (▼) ions measured in KCl and NaCl solutions individually for different membrane thicknesses. The right axis shows resulting selectivity of K⁺/Na⁺, represented by grey unfilled squares. The error bars represent an average of at least two measurements each.
selectivity (Fig. 5b). While the initial values of selectivity were 2.42 ± 0.14 possibly due to absorption of ions (Fig. SI 1), they stabilised at 1.85 ± 0.17. This value of was relatively stable for over 35 h, and is understood to be a combination of factors.

We begin with a 1:1 ratio of Na\(^+\) and K\(^+\) ions on the concentrate side, and MilliQ water on the dilute side. Transport from the concentrate to dilute stream is governed by two factors, the ion concentration difference over the membrane and the difference in diffusion constant in the membrane. For traditional permselective ion exchange membranes the concentration difference is governed by the Donnan equilibrium.

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**Fig. 5.** In (a), K\(^+\) (\(\Delta\)) and Na\(^+\) (\(\triangledown\)) concentrations (mM) are shown for the hot-pressed PSS-PVA membrane when placed in between a solution of mixed KCl and NaCl on one side and DI water on the other (refer Fig. 2). The left and right axes represent the diluate (\(\triangledown\)) and concentrate (\(\Delta\)) respectively, against time (hours) on the x-axis. (b) Represents the diluate concentration based selectivity. The error bars represent an average of two measurements.

**Fig. 6.** In (a) and (c), K\(^+\) (\(\Delta\)) and Na\(^+\) (\(\triangledown\)) concentrations (mM) are shown for two commercial membranes, Neosepta CMX and Ralex CMH, respectively when placed in between a solution of mixed KCl and NaCl on one side and DI water on the other (refer Fig. 2). The left and right axes represent the diluate (\(\triangledown\)) and concentrate (\(\Delta\)) respectively, against time (hours) on the x-axis. (b) and (d) represent the diluate concentration based selectivity for the two membranes. The error bars represent an average of at least two measurements.
Following the Donnan equilibrium, assuming the membrane adapts quickly to equilibrium conditions, a 1:1 starting concentration of a salt mixture results in a 1:1 adsorption in the membrane and hence a 1:1 transport of ions. This result is obvious from the two tested commercial membranes that show a long term flux selectivities for K\(^+\)/Na\(^+\) of 0.99 ± 0.07 and 0.78 ± 0.03 for Ralex CMH and Neosepta CMX respectively (Fig. 6a–d). The saloplastic membrane clearly behaves differently. Here the ratio of activities across the PSS-PVA membrane is no longer 1. Hence, theoretically it should result in a situation where the system tries to balance this effect by decreasing the driving force for the fastest ion. However, apparently it does not significantly slow down, potassium is continuously diffusing significantly faster through the membrane than sodium. The measured ratio of fluxes is higher than the ratio of their diffusion speeds in water. This suggests that the transport in the ionic environment of the membrane is less governed by interactions with the counterions of the membrane. This may be due to the large amount of ionic groups in the bulk of the saloplastic film. Whereas all ionic groups in the commercial membrane contribute to the exclusion effect, in saloplastic, even if this is an excess of >1meq/g, it is only a minor amount of the total ionic groups. The bulk of the membrane volume can therefore behave different as compared to the inert bulk of the ion-exchange membranes.

In the resistance experiment, diffusion governs the transport through the membrane. Since the membranes were virtually non-permeable to water at 2.5 bars, convective transport can be neglected. The crystal radii of Na\(^+\) and K\(^+\) are 97 p.m. and 133 p.m. respectively [46]. However, Na\(^+\) is a kosmotrope in the Hofmeister series which attracts and immobilizes water around itself strongly, with a greater apparent molecular weight than in its anhydrous state (Fig. 2). These water molecules move along with the Na\(^+\) ion, reducing the effective diffusion. K\(^+\) is a chaotrope with a dynamic hydration shell around it [47]. The Stoke’s radius of Na\(^+\) is much higher at 195 p.m. while that of K\(^+\) remains 133 p.m. The diffusion coefficients of Na\(^+\) and K\(^+\) in water are respectively 1.33 and 1.96 (10\(^{-9}\) m\(^2\)/s) at 20 °C [48], so that K\(^+\) selectively diffuses 1.47 times faster.

The measured selectivity values of 1.85 ± 0.17 were consistent and reproducible. Hence, in addition to the difference in their speeds in water, there is a kinetic selectivity of the membrane material. When K\(^+\) is adsorbed, its soft shell does not hinder the diffusion as much as the hard shell of water around Na\(^+\) [49]. For diffusion in a solid material, the size is expected to be an important factor. However, the pure ion size is not significant in comparison to that of the water shell.

In order to explain the different behaviour of the salt transport through the saloplastic membranes as compared to commercial cation exchange membranes, some hypotheses were formulated. The differences in the hydration shells of these cations also correspond to their migration in the commercial membranes as compared to the inert bulk of the ion-exchange membranes.

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In order to explain the different behaviour of the salt transport through the saloplastic membranes as compared to commercial cation exchange membranes, some hypotheses were formulated. The differences in the hydration shells of these cations also correspond to their interaction with polar groups in the bulk. An OH\(^-\) edge in graphene membranes allowed K\(^+\) permeation while rejecting Na\(^+\) [33]. Charged mosaic membranes also showed a selectivity owing to the interaction of the ions with oppositely charged and polar groups [50]. Our PSS-PVA plastic membranes too are made of a combination of cationic and anionic groups, and the polarity of the amine group may favour the K\(^+\) selectivity as in the case of OH\(^-\). Further, amine groups in their aqueous phase are surrounded by OH\(^-\) ions, which interact favourably with the dynamic shell of water molecules around K\(^+\) ions, unlike with Na\(^+\).

As a result of the different interactions, the PSS-PVA membrane has a preference for K\(^+\) without completely rejecting Na\(^+\) ions, leading to enrichment for K\(^+\) but still retaining low quantities of Na\(^+\). This is ideal for agricultural purposes indicated at the start, where a reduction in Na\(^+\) concentration is a need without complete elimination, at a steady state [24]. While there are no commercial membranes selecting K\(^+\) over Na\(^+\), the advent of such a membrane is very promising.

A simple hot-pressing approach, not requiring any organic solvents, was used to process a complex precipitate of PSS-PVA into a dense saloplastic sheet with effective surplus of negative charge. Such a plastic has a water uptake of 42% and an effective cation exchange capacity of 1.1 ± 0.4 mmol/g. Resistance-based selectivity revealed a preference towards K\(^+\) over Na\(^+\), which was further confirmed by long term ion flux values, showing a K\(^+\) over Na\(^+\) cation (monovalent) selectivity. The authors attribute this to the hydrated shell sizes of the ions, wherein Na\(^+\) has a stronger adhesion to water molecules as opposed to K\(^+\) ions, where they are mobile. The absence of the selectivity for two commercial cation exchange membranes shows that saloplastics behave differently, favouring diffusional selectivity rather than generally observed concentration based selectivity, i.e. a transport that is governed by the Donnan equilibrium. In addition to this, it is hypothesized that the presence of amine groups in the complex adds to selectivity for K\(^+\). Other advantages include the simple and reproducible fabrication, and the possibility of scaling up when compared to other membranes [35]. Hence, the membrane is potent to be used in applications where the ratio of K\(^+\)/Na\(^+\) needs to be enhanced, while not completely removing Na\(^+\). It would therefore be suitable for agricultural feed water adjustment processes to irrigate plants while maintaining a healthy salt balance.

CRediT author contribution statement

Ameya Krishna B: Investigation, Validation, Data curation, Writing - original draft. Harmen Zwijnenberg: Investigation, Methodology, Writing – review and editing. Saskia Lindhoud: Conceptualization, Visualization, Methodology, Project Administration, Supervision. Wiebe M. de Vos: Conceptualization, Visualization, Project Administration, Funding acquisition, Supervision.

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Declaration of competing interest

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

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Appendix A. Supplementary data

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