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Simultaneous recovery of nutrients and hydrogen via electroconcentration

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Abstract

As the global shift toward circular economy accelerates, recovering nutrients and energy from waste streams has become increasingly critical. This investigation explores electroconcentration (EC) as a strategy for recovering multiple nutrients and hydrogen (H_2) from hydrolysed urine under continuous operation. The system achieved high removal and recovery efficiencies for key ions: 79.87% for NH_4^+, 75–88% for Na^+, K^+, and Cl^-, and over 50% for PO_4^{3-} and SO_4^{2-}, with up-concentration factors ranging from 3.3 to 5.4. A peak NH_4^+-N concentration of 24.6 g/L was obtained in the concentrate. Simultaneously, H_2 was recovered at 5.40 m^3/m^3·d, offering an energy offset of 4.42 kWh/kg N recovered. The system maintained stable performance over 168 h of continuous operation. These results highlight EC as a viable platform for integrated nutrient and energy recovery, offering strong potential for decentralised wastewater treatment and circular resource management.

1 Introduction

Global population growth, which is projected to reach 10 billion by 2064, is driving unprecedented demand for sustainable nutrient management solutions [1]. Conventional fertiliser production relies on energy-intensive ammonia synthesis and finite phosphate rock reserves, which faces significant environmental and geopolitical challenges [2,3]. Concurrently, wastewater treatment systems struggle with rising energy demands and stringent nutrient discharge limits, prompting interest in decentralised resource recovery [4–6]. Human urine, though constituting just 1% of domestic wastewater volume, contains a wide range of nutrients: 79% of nitrogen (N), 47% of phosphorus (P), and 71% of potassium (K) [7]. This high nutrient density and favourable electrochemical properties (e.g., conductivity, buffering capacity) make urine an ideal candidate for advanced recovery technologies [8–10]. While struvite precipitation and ammonia stripping have demonstrated partial nutrient recovery, they often require chemical inputs or multi-stage processing [11], thereby precluding their widespread adoption and deployment.

As a potential alternative, electrochemical systems can offer a paradigm shift by enabling simultaneous nutrient concentration and energy recovery [12]. Among the broad portfolio of these technologies, electroconcentration has shown particular promise by concentrating ions into a liquid fertiliser while co-producing hydrogen (H_2) [13]. Notably, this approach addresses two critical knowledge gaps: (1) the need for sustainable nutrient sources to replace linear production methods and (2) the optimisation of wastewater treatment under increasing hydraulic and nutrient loads. An electroconcentration set-up consists of three chambers: anodic, cathodic, and a middle chamber, also called the concentrate chamber. The anodic and concentrate chambers are separated with a cation exchange membrane (CEM), while cathodic and concentrate chambers use an anion exchange membrane (AEM).

An external charge is applied, inducing the migration of cations, such as ammonium nitrogen (NH_4^+-N), sodium (Na^+), and K^+, and anions, such as phosphate (PO_4^{3-}) chloride (Cl^-), and sulphate (SO_4^{2-}), through their respective membranes and concentrating them in the middle chamber [14]. Along with ions, ion-bound water also moves into the concentrate chamber, leading to overflow, which can be collected [15,16]. The resulting concentrate contains a high concentration of recovered nutrients, offering a potential alternative to conventional fertilisers. Simultaneously, H_2 is generated as a by-product in the cathodic chamber, which can be collected and stored for various energy-related applications. The recovery of NH_4^+-N in an electroconcentration system primarily depends on the load ratio (L_N), defined as the ratio of the applied current density to the theoretical current density required to migrate all NH_4-N through the CEM [17,18]. As hydrolysed urine contains a high concentration of NH_4^+-N (1.5–10 g/L), the L_N is typically kept below one, resulting in its partial recovery [11,19]. Additionally, the presence of competing ions, such as Na^+ and K^+, further reduces NH_4^+-N recovery [20,21].

To enhance NH_4-N recovery, significant advancements in reactor design and operational strategies are required. Chen and co-researchers reported that 80% segregation of urine, followed by separate treatment, could eliminate the need for nitrogen removal technology in conventional wastewater treatment plants (WWTPs) [3]. Furthermore, a 75% segregation of urine could increase the treatment capacity of WWTPs by 48% due to reduced nitrogen loading. Similarly, Badeti and co-researchers found

that at 75% urine segregation, the treatment capacity of WWTPs could be doubled [22]. However, excessively high urine segregation may negatively impact biological treatment processes by reducing sludge flocculability and settleability, thereby disrupting the removal of organic matter, N, and P. These findings suggest that source-separating urine at an optimal level can effectively recover nutrients while increasing WWTP efficiency. An alternative strategy is to segregate 100% urine while targeting up to 80% of NH_4^+-N removal and recovery via electroconcentration. The treated urine could then be reintroduced into the remaining sewage stream to maintain sufficient nutrient levels for biological processes.

In light of the above discussion, the present research investigates the electroconcentration of source-separated hydrolysed urine. Initial experiments were conducted in semi-continuous mode to determine the optimal L_N for achieving 80% of NH_4^+-N removal efficiency in a single pass. Subsequently, the reactor was operated in continuous mode to evaluate its feasibility for long-term field-scale applications. Additionally, this study explores the recovery of H_2 gas produced in the cathodic chamber. To the best of the authors' knowledge, this is the first investigation on electroconcentration that has been specifically designed to achieve adequate NH_4^+-N removal, enabling both nutrients recovery followed by direct urine discharge while maintaining sufficient nutrient levels for biological treatment.

2 Materials and methods

2.1 Materials used

All the reagents used in this investigation to prepare synthetic urine was procured from Loba Chemie Pvt. Ltd., India. The feed contained (in g/L) Na_2SO_4 (2.3), $NaH_2PO_4.H_2O$ (2.73), NaCl (3.6), KCl (4.2), $NH_4CH_3CO_2$ (9.6), NH_4HCO_3 (17.8), and NH_4OH (25% liquid, 5 mL/L).

2.2 Reactor fabrication and operation

The reactor schematics consisted of three chambers: anodic, cathodic, and concentrate. Acrylic sheets measuring 14 cm × 14 cm × 2.6 cm were grooved into a cylinder of 11 cm diameter and 2.2 cm depth, providing a final working volume of 190 mL for both anodic and cathodic chambers. Another acrylic sheet (14 cm × 14 cm and 10 mm thickness) was bored throughout at the centre with a diameter of 11 cm and it was utilised as the concentrate chamber. The anodic and concentrate chambers were separated using a CEM (Ralex, CMHPES-TL), while an AEM (Ralex, AMHPES-TL) was used to separate the cathodic and concentrate chambers (Fig. 1). The effective exposed surface area of the membranes was 95 cm^2. Before application in the EC cell, the membranes were pre-treated by soaking overnight in a 5% (w/w) NaCl solution. The middle chamber was filled with glass beads (diameter 5 ± 1 mm) to safeguard the membranes from bulking, resulting in a final working volume of 55 mL for the concentrate chamber. The concentrate overflowed from the middle chamber was collected in a separate bottle and stored for further analysis. Meanwhile, the H_2 gas generated was collected via a separate pipe connected to the cathodic chamber as shown in Fig. 1 (b).

Mixed metal oxide-coated titanium electrodes (8 cm × 8 cm) were employed as anode and cathode. Synthetic hydrolysed urine with composition described in an earlier investigation was used as a feed with slight modification [20] as mentioned in materials section. The urine thus prepared contained 5.3 g/L of NH_4^+-N. Further, it was assumed that complete removal of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions was achieved via precipitation during hydrolysis. The reactor was initially operated in semi-continuous mode (treating 1 L of urine) to determine the required L_N targeting 80% of NH_4^+-N removal at an applied current density of 155 A/m^2. Afterwards, the reactor operation was shifted to continuous mode and operated for 168 h. Table 1 summarises the different operating conditions investigated in the present experiments.

Table 1
Key parameters investigated in the present experiments

Operating strategy	Flow rate (L/d)	Current density (A/m^2)	Load ratio	HRT€, ¥ (h)	NH_4-N loading rate¥ (mmol/L.d)
Semi-continuous	3.45	155	1	2.6	3443
	2.88		1.21	3.2	2869
Continuous	2.88		1.21	3.2	2869

€HRT: Hydraulic retention time; ¥Normalised over combined anolyte and catholyte volume

In previous reports on electroconcentration, either the electrolyte was fed into the anodic chamber, with anolyte and catholyte streams intermixed, or during individual mixing, no focus was paid for H_2 collection, thus wasting this valuable product [14,20,21]. However, in present research, a modified flow pattern was implemented. Hydrolysed urine was first introduced into the cathodic chamber, and separate mixing of anolyte and catholyte streams was performed to facilitate the efficient collection of H_2. Additionally, this flow pattern enabled the recovery of NH_4^+-N, which is often lost otherwise to the catholyte through use of the AEM due to its lower perm-selectivity, particularly as the concentrate becomes highly saturated.

2.3 Sampling, chemical analysis and calculations

Samples were collected from the effluent of respective chambers (n = 3) and were analysed to quantify the presence of different ions. During the semi-continuous reactor operation, the initial and final samples were analysed to evaluate the removal efficiency. At the same time, the concentrate produced in the middle chamber, collected in the collection bottle, was mixed and analysed to gain insight into the recovery of different ions. The electrical power consumption was estimated using the current (fixed) and voltage data recorded at intervals of 30 min. During continuous operation, samples were collected every 24 h and analysed. Also, the power consumption in continuous mode was evaluated using the current (fixed) and voltage data averaged over the sampling interval [14]. The pH, NH_4^+-N, and electrical conductivity were analysed using probes fixed on a benchtop set-up (Thermofisher Scientific Co., USA). The presence of other ions was detected using ion chromatography (IC, ECO 930 Metrohm, Herisau, Switzerland).

The collected gas was analysed using an Agilent 7890A gas chromatography (GC) system (Agilent Technologies, Singapore) consisting of a thermal conductivity detector equipped with MolSieve 13X (60/80 Mesh size, stainless steel tubing, 3.05 m × 1/8" × 2.0 mm, Pre-conditioned - JW) column. The NH_4-N removal and recovery rates were normalised over the total reactor volume (435 mL). The ion transport efficiency (tE_n), defined as the contribution of selected ion from the total charge migrated over the membranes, was estimated using Eq. 1:

$$tE_n\ (\%) = \frac{\frac{J_n}{M} * Z * F}{j_{app}} \times\ 100\% \quad \text{Eq. 1}$$

Here, J_n represents the migration rate of the ion in $g/m^2{\cdot}s$ normalised over the membrane area to the concentrate chamber, *M* is the molar mass (g/mol) of the ion under investigation, and *Z*, *F*, and j_{app} denote the charge, Faraday's constant (C/mol), and applied current density (A/m^2), respectively. Further, the L_N was estimated using Eq. 2:

$$L_N = \frac{j_{app}}{c_{NH_4-N,\ inlet} * Q * \frac{F}{A_m}} \quad \text{Eq. 2}$$

Here, $c_{NH_4-N,\ inlet}$ is the NH_4-N concentration in the feed (mol/m^3), j_{app} is the applied current density (A/m^2), *Q* is the influent flow rate (m^3/s), and *F* and A_m are the Faraday's constant and membrane area (m^2), respectively. The specific energy consumption for nitrogen removal was estimated using Eq. 3.

$$Energy\,Consumption\ \left(kWh/kgNH_4^+-N\right)=\frac{I\int Vdt}{mass\ of\ NH_4^+-N\ removed\ from\ dilute}\times\frac{1}{1000}$$ Eq. 3

Where *I* is applied current and *V* is voltage recorded over time *dt*.

3 Results and discussions

3.1 Effect of load ratio on NH_4^+-N removal and recovery

The reactor was initially operated in a semi-continuous mode to evaluate the performance under varying L_N. The primary objective was to achieve an LN corresponding to 80% of NH_4^+-N removal efficiency. As illustrated in Fig. 2 (a), at an initial L_N = 1, the NH_4^+-N removal efficiency was 68.39 ± 0.47%, with a removal rate of 35.08 ± 0.24 kg NH_4^+-N/m^3·d. Simultaneously, 57.23 ± 6.0% of NH_4^+-N was successfully recovered in the concentrate chamber, translating to a recovery rate of 26.11 ± 0.16 kg NH_4^+-N/m^3·d and a transport efficiency of 61.54 ± 0.39% (Fig. 2 (b)). Upon increasing the L_N to 1.21, the NH_4^+-N removal efficiency improved significantly to 80.7 ± 0.47%, with a corresponding removal rate of 34.5 ± 0.20 kg NH_4^+-N/m^3·d. This enhancement in removal efficiency is attributed to the increased hydraulic retention time (HRT), which facilitates prolonged contact between the influent and the CEM, thereby improving NH_4-N migration.

Concurrently, NH_4^+-N recovery efficiency rose to 72.40 ± 1.54%, yielding a recovery rate of 31 ± 0.66 kg NH_4^+-N/m^3·d and a transport efficiency of 73 ± 1.56%. It was observed that the removal rate remained almost same with an increase in L_N; however, the recovery rate increased significantly. This can be attributed to a comparatively less increase observed in NH_4^+-N removal efficiency (from ~ 68% to 80%). In contrast, the prolonged contact time increased recovery efficiency (~ 57% to 72%), thus increasing the recovery rate. A similar observation was also noticed regarding energy requirements, which rose from 16.2 ± 2.2 to 20.1 ± 1.0 kWh/kg NH_4^+-N removed as the L_N was increased from 1 to 1.21. These findings suggest that an L_N of 1.21 is optimal for achieving target NH_4^+-N removal of 80%, making it a suitable operating parameter for transitioning the system to continuous mode of operation.

3.2 Continuous mode operation

Following the semi-continuous reactor operation, the system was transitioned to continuous mode and operated for 168 h while monitoring key parameters. The initial NH_4^+-N removal efficiency was approximately 82%, which is consistent with semi-continuous results. However, after 72 h, it marginally declined to an average of 79.87 ± 0.94% before stabilising (Fig. 3). Simultaneously, the NH_4^+-N recovery efficiency averaged at 69.06 ± 4.07%, corresponding to a 59.84 ± 2.76% transport efficiency. Meanwhile, around 10% of NH_4^+-N was lost in the system (removed but not recovered). The system achieved remarkable NH_4^+-N removal and recovery rates of 29.98 ± 0.65 kg NH_4^+-N/m^3·d and 25.4 kg NH_4^+-N/m^3·d, respectively, which is significantly surpassing the biotic counterpart (bioelectroconcentration cell) with a recovery rate of only 7.18 kg NH_4^+-N/m^3·d [23]. Moreover, the NH_4^+-N flux through the CEM (~ 1163 g/m^2·d) in this investigation was notably higher than that reported for hybrid electrodialysis and membrane contactor set-up (739 g/m^2·d), a bipolar electrodialysis pilot (222 g/m^2·d), and hybrid Donnan Dialysis-Electrodialysis configurations with a flux of 99.1 g/m^2·d [24–27].

Figure 4 (a) illustrates the NH_4^+-N removal and recovery efficiency over time. At 48th h, the NH_4^+-N recovery efficiency peaked at 74.92% before stabilising at an average of 69.06%. The initially higher recovery can be attributed to the low concentration of competing ionic species in the concentrate. However, as time progressed, the concentrate became increasingly saturated with cations and anions, leading to reduced flux rates. For instance, the NH_4^+-N flux across the CEM was 1245.53 g/m^2·d at 48 h, which declined to an average of 1162.88 g/m^2·d after 120 h, further indicating the impact of ionic saturation. Similarly, the NH_4^+-N removal efficiency was initially high (~ 82%) at 48 h but later decreased to an average of ~ 79% after 120 h. This decline can also be attributed to NH_4^+-N leakage from the concentrate into the cathodic chamber due to the lower perm-

selectivity of the AEM, which affected the overall removal efficiency. After 120 h, the NH_4^+-N concentration in the effluent catholyte increased to 5.5 g/L (influent = 5.3 g/L). While the reactor geometry allows for partial recovery of lost ions as the catholyte flows into the anodic chamber, a slight decrease in overall removal efficiency was still observed. To mitigate this issue, a relatively higher initial NH_4^+-N removal efficiency should be targeted during semi-continuous operation to compensate for losses.

The recovered NH_4^+-N was effectively concentrated and collected from the middle chamber as overflow. Figure 4 (a) illustrates the variation in NH_4^+-N removal and recovery over the entire duration of the experiment. An initial increase in concentration was followed by a saturation phase, resulting in an average NH_4^+-N concentration of 24.60 ± 0.13 g/L, approximately 4.65 times the influent concentration. The NH_4^+-N concentration observed in this study was higher than in previous investigations, where bioelectroconcentration achieved 21.2 g_N/L from urine, and an air-cathode bio-electroconcentration set-up yielded 11.6 g_N/L. Additionally, the NH_4^+-N concentration in this investigation was comparable to 28.49 g_N/L (or 2.035 M total ammonia nitrogen) reported by Jermakka and co-researchers, using electroconcentration system with 62% recovery efficiency and a 3.58-fold concentration increase at an applied current density of 80 A/m² [20,28,29].

These findings highlight that nitrogen recovery via electroconcentration is a delicate balance between applied current density and up-concentration efficiency. As current density increases, water flux to the concentrate chamber also rises, leading to dilution of NH_4^+-N concentration. For instance, Jermakka and co-researchers reported an increase in water flux to 16.4% at 80 A/m^2, compared to 9.6% at 40 A/m^2. A similar trend was observed in the present investigation, where the water flux reached ~ 16%, limiting higher up-concentration factors [20]. The water flux in the present investigation was observed to be less than previous investigation as the build-up of pressure in the cathodic chamber was minimised by collecting the H_2 gas produced. Furthermore, the electrical conductivity of both the concentrate and the final effluent (dilute) was monitored. Over the time, conductivity of the concentrate increased due to ion migration, peaking at 126 ± 0.47 mS/cm (Fig. 4 (b)). Meanwhile, the conductivity of the effluent remained stable at approximately 12.5 mS/cm. The electrical conductivity observed in this investigation was slightly lower than the 131 ± 4 mS/cm as reported by Jermakka and co-researchers [20]. This difference can be attributed to the lower L_N (< 1) used in the previous research, which allowed for more efficient NH_4^+-N migration compared to competing smaller-sized ions such as H^+ at higher L_N, albeit at lower overall NH_4^+-N removal and recovery efficiency.

3.3 Recovery of other ions

The system facilitated the simultaneous recovery of different cations and anions in the concentrate. For instance, a removal efficiency and recovery efficiency of 82.2 ± 3.5% and 75.65 ± 3.2% were achieved for Na^+, respectively. Other monovalent ions, such as K^+ and Cl^-, were also significantly removed (92.7 ± 5.6% and 87.2 ± 3.9%, respectively) and effectively concentrated, with recovery efficiencies of 85.9 ± 6.6% and 81.88 ± 4.2%, respectively (Table 2). The final concentrations of Na^+ and K^+ in the concentrate were 12.24 ± 0.35 and 11.94 ± 0.66 g/L, respectively, corresponding to approximately 4.78 and 5.42-fold increase compared to their influent concentrations. In addition to monovalent ions, multivalent ions such as PO_4^{3-} and SO_4^{2-} were also partially removed, with removal efficiencies of 56.7 ± 2.5% and 70.2 ± 2.7%, respectively, and recovery efficiencies of 52.12 ± 3.6% and 63.18 ± 3.2%, respectively. The concentrations of Cl^-, PO_4^{3-} and SO_4^{2-} in the concentrate were 21.60 ± 0.81 g/L, 5.40 ± 0.14 and 6.20 ± 0.16 g/L, respectively, corresponding to 5.17, 3.29 and 4.03-fold up-concentration.

The up-concentration factors observed in this investigation were higher than those reported in previous investigations, which achieved 4.00, 4.28, 4.66, 3.88, and 2.66-fold up-concentrations for Na^+, K^+, Cl^-, SO_4^{2-}, and PO_4^{3-}, respectively. This higher up-concentration efficiency can be attributed to the reduced water flux through the membranes in the present investigation, minimising dilution effects in the concentrate. Thus, the system presents an excellent choice for simultaneous nutrient recovery. Notably, the system allowed the removal and recovery of PO_4^{3-}, which is otherwise a significant challenge in conventional biological processes. Thus, utilising the present system to pre-treat urine before mixing it with the remaining sewage can be a suitable strategy for adequate nutrient recovery and increasing the treatment capacity of WWTPs.

Table 2
Removal and recovery of different ions during continuous reactor operation

Ion	Initial Concentration (g/L)	Removal efficiency (%)	Recovery Efficiency (%)	Concentrate Concentration (g/L)
NH_4^+-N	6.3 ± 0.1	79.8 ± 0.9	69.1 ± 4.1	24.6 ± 0.1
Na^+	2.5 ± 0.5	82.2 ± 3.5	75.6 ± 3.2	12.2 ± 0.4
K^+	2.2 ± 0.3	92.7 ± 5.6	85.9 ± 6.6	11.9 ± 0.6
Cl^-	4.2 ± 0.2	87.2 ± 3.9	81.8 ± 4.2	21.6 ± 0.8
PO_4^{3-}	1.7 ± 0.2	56.7 ± 2.5	52.1 ± 3.6	5.4 ± 0.1
SO_4^{2-}	1.5 ± 0.1	70.2 ± 2.7	63.2 ± 3.2	6.2 ± 0.2

3.4 Hydrogen recovery

In addition to nutrient recovery, the EC system was engineered to enable simultaneous H_2 production through water electrolysis at the cathode, governed by the hydrogen evolution reaction (HER). During continuous operation, the system achieved a H_2 production rate of 5.40 m^3 H_2 per m^3 of urine treated per day. The gas chromatography analysis confirmed that the produced gas was highly pure, containing > 85% H_2, with no detectable traces of methane (CH_4), carbon dioxide (CO_2), or carbon monoxide (CO). This indicates effective suppression of side reactions and high electrochemical selectivity for hydrogen generation under the applied current density (155 A/m^2). Such high purity makes the collected H_2 suitable for downstream applications including PEM fuel cells, catalytic combustion, industrial use, or blending with natural gas grids.

The energy value of the recovered H_2 can be estimated based on its lower heating value of ~ 10.8 MJ/m^3. At a recovery rate of 5.40 m^3/m^3·d, the energy output equates to approximately 58.32 MJ/m^3, or 16.2 kWh per m³ of urine treated. Normalized over NH_4^+-N recovery, this translates to 4.42 kWh of energy recovered as H_2 per kg of NH_4^+-N recovered. This represents a significant energetic co-benefit, offsetting a portion of the energy required for electroconcentration, which can improve overall process economics and sustainability. Importantly, H_2 recovery in this system served a dual role. Beyond energy valorisation, it stabilised pressure dynamics within the cathodic chamber by continuously venting the evolved gas. This helped reduce internal hydraulic resistance and mitigated water crossover into the concentrate chamber, thereby preserving high up-concentration efficiency and membrane selectivity over extended operation. Previous investigations have shown that uncollected H_2 accumulation can increase cathodic pressure, drive water flux and dilute the nutrient concentrate [20]. The intentional collection of H_2 in this setup thus contributed to enhanced operational stability and ion transport performance.

When integrated into a decentralised urine treatment framework, the simultaneous production of H_2 alongside nutrient recovery offers a pathway to partial energy recovery and circular resource utilisation. Although the energy offset is currently modest relative to total input, further enhancements, such as improved electrode materials, optimised current densities, and coupling with renewable electricity, can further improve energy efficiency. Overall, this investigation establishes H_2 as a strategic co-product in electrochemical nutrient recovery systems, reinforcing the case for multi-resource recovery platforms in future wastewater infrastructure.

3.5 Scale-up implications

The system employed in the current investigation presents a promising option for scale-up. The energy requirement for NH_4^+-N removal was 22.56 ± 0.60 kWh/kg NH_4^+-N. Similar to electrodialysis, this energy demand is expected to decline significantly by implementing a stacked configuration with multiple concentrate chambers. For instance, in a previous investigation employing stacked bi-polar membrane electrodialysis, the energy demand reduced from 92.8 MJ (25.8 kWh) to 25.8 MJ (7.2 kWh) per kg

N [26,30,31]. Thus, it can be expected that the energy demand in current set-up will also be reduced significantly, thereby making the system economically more viable.

In present investigation, the NH_4^+-N concentration reached 24.6 g/L (~ 2.5%) in the recovered product. In the current set-up, an L_N = 1.21 was used, targeting 80% NH_4^+-N removal in a single pass, necessitating a high current density of 155 A/m^2. However, a lower L_N could significantly increase the recovered NH_4^+-N concentration. Brewster and colleagues predicted via theoretical modelling that at a L_N of 0.46, the product concentration could reach 4.9 M of total ammonium nitrogen in the middle chamber, making the system more practical for field applications [21]. Future research should focus on optimising L_N and implementing stacked configurations to reduce energy consumption and improve the feasibility of large-scale deployment. Table 3 presents a comparison of nutrients recovery via EC and other technologies.

Conclusion

This investigation demonstrated the feasibility of electroconcentration for nutrient recovery from source-separated hydrolysed urine while simultaneously producing H_2 as a valuable by-product. The system achieved a NH_4^+-N removal efficiency of 79.87 ± 0.94% and a recovery efficiency of 69.06 ± 4.07%, with a maximum NH_4^+-N concentration of 24.6 ± 0.13 g/L in the concentrate. Continuous-mode operation confirmed the stability and scalability of the process, with minimal interference from competing ions (Na^+, K^+). Additionally, H_2 gas was recovered at a rate of 5.40 m^3/m^3·d, highlighting the dual benefit of nutrient recovery and renewable energy production. The specific energy consumption for NH_4^+-N removal was 18.14 ± 1.27 kWh/kg NH_4^+-N, suggesting that EC can be a viable alternative to conventional nutrient recovery methods. However, further optimisation of reactor design and operational parameters, especially L_N, is necessary to enhance efficiency and reduce energy consumption. Future work should focus on scaling up the process, evaluating long-term performance in real-world conditions, and integrating the system with existing wastewater treatment infrastructure to maximise its environmental and economic benefits.

Table 3
Comparison of nitrogen recovery using different electrochemical technologies from urine

Technology	Initial nitrogen concentration (g/L)	Recovery efficiency (%)	Concentrate nitrogen (g/L)	Nitrogen flux ($mol/m^2 \cdot h$)$	Energy demand (kWh/kgN)	H_2 recovery	Reference
Bipolar Membrane Electrodialysis	3.7	67.5	-	2.2	25.7	-	26
Combined struvite precipitation-air stripping-acid scrubbing	5.6	93.0	-	-	54.8	-	32
Electrochemical Stripping#	4.0	92.7	-	3.0	8.5	-	33
Electrochemical stripping#	~ 4.7$	78.4	10.6	1.0	33.1	-	34
Electrochemical cell#	4.8	76.0	-	0.8	12.7	-	35
	5.1	58.0	-	0.7	14.7	-	
Electroconcentration cell	7.9	62.0	28.5	-	12.7	-	20
Electroconcentration cell	5.3	69.1	24.6	3.46	18.1*	5.4 $m^3/m^3 \cdot d$	This work

#Requires post treatment with chemical for nitrogen recovery, *After adjusting for energy by hydrogen recovery, $Values calculated from data provided

Declarations

Author Contribution

Anil Dhanda – Investigation, Conceptualization; Visualization; Validation; Writing – original draft; Software support; Lakshmi Pathi Thulluru – Investigation, Conceptualization; Visualization; Validation; Writing – original draft; Software support; Shamik Chowdhury – Writing – review & editing; B. K. Dubey – Resources; Supervision; Writing – review & editing; M. M. Ghangrekar – Resources; Funding acquisition; Supervision; Project administration; Writing – review & editing, Debkumar Chakraborty – Investigation, Visualization, Validation, Formal analysis, Gorakhanath Jadhav – Investigation, Visualization, Validation, Paula Sfirloaga - Resources, Project administration, Funding acquisition; Narcis Duteanu– Writing – review and editing, Resources, Project administration, Funding acquisition, Supervision

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Data Availability

All data supporting the findings of this study are available within the paper.

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Figures

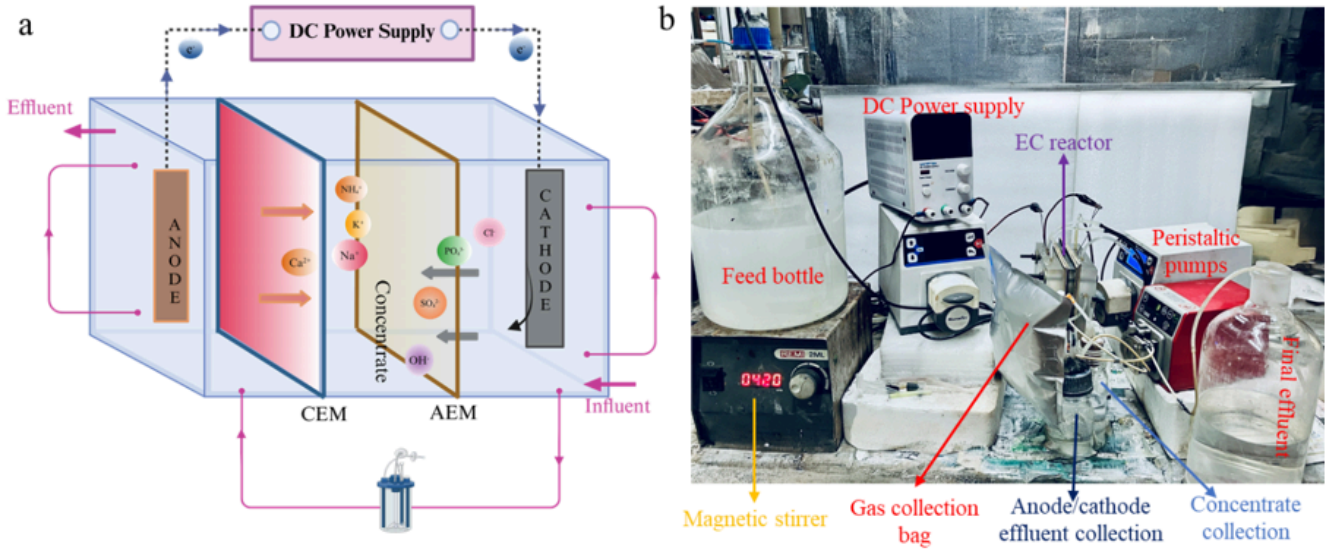


Figure 1

(a) Schematics and (b) digital picture of the actual electroconcentration set-up employed in this experiment.

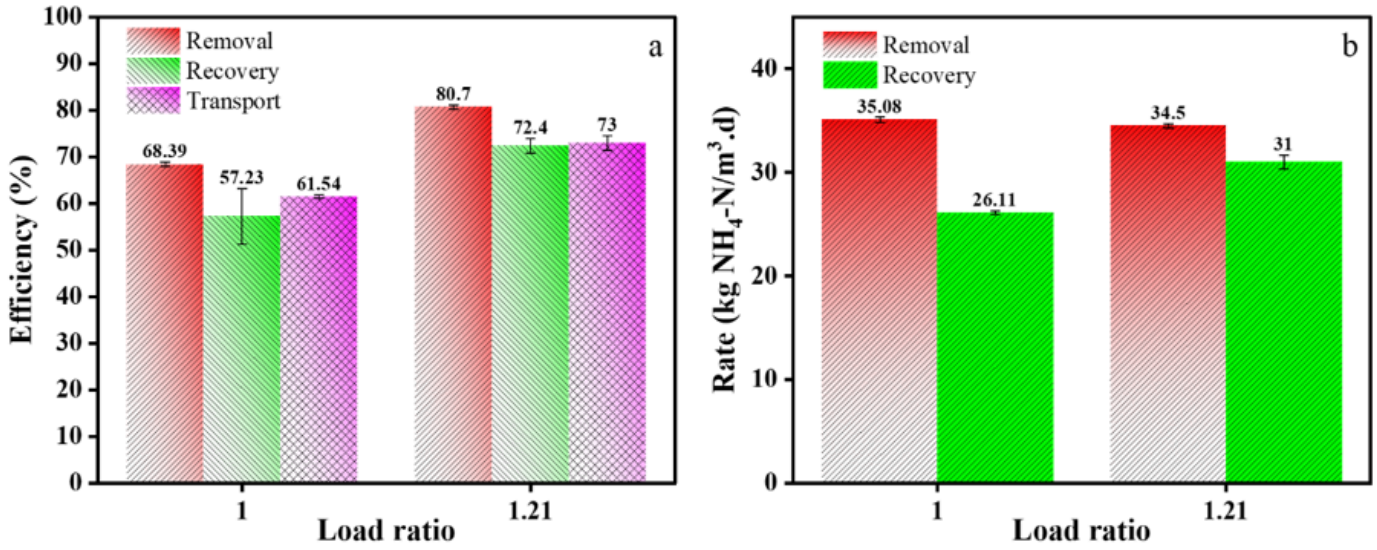


Figure 2

(a) Removal, recovery and transport efficiencies and (b) removal and recovery rates during the semi-continuous mode operation

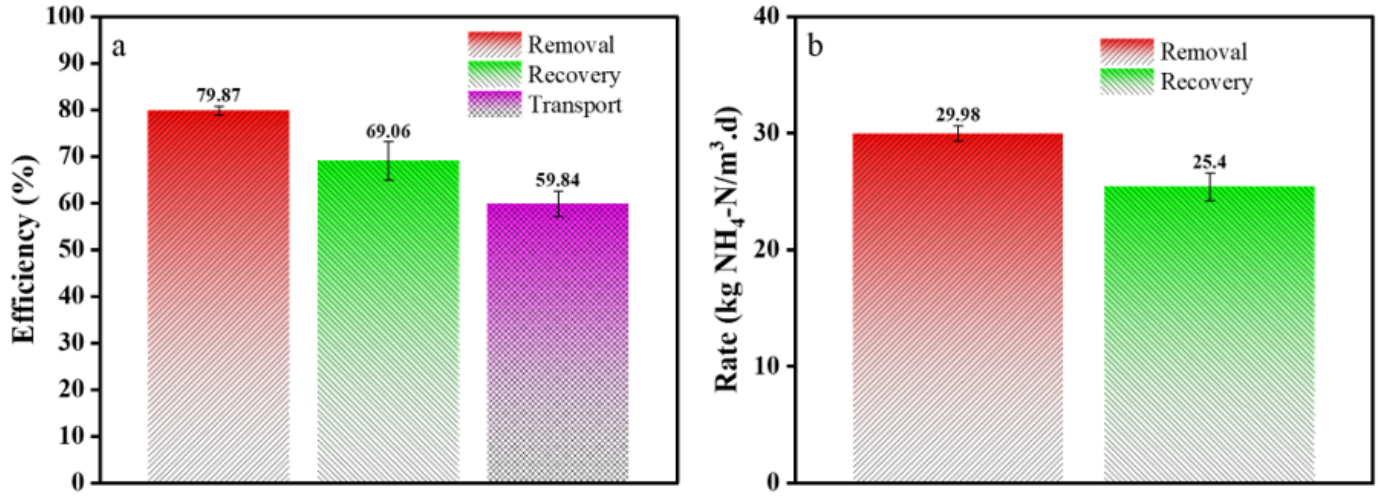


Figure 3

(a) Removal, recovery, and transport efficiency and (b) removal and recovery rates during continuous mode operation

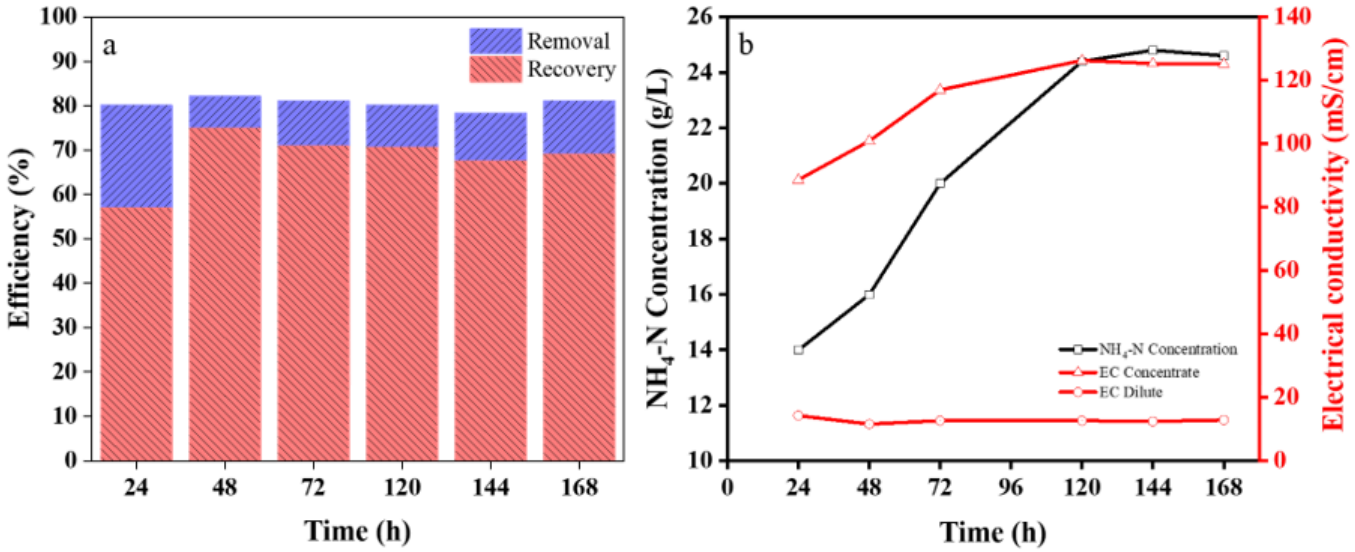


Figure 4

(a) NH_4^+-N removal and recovery efficiency and (b) concentration and electrical conductivity variation observed during continuous operation