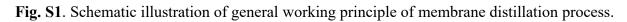
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[†]Electronic supplementary information (ESI)

Remediation and recycling of inorganic acids and their green alternatives for the sustainable industrial chemical processes

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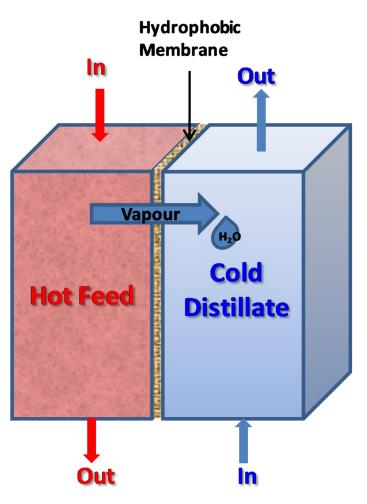
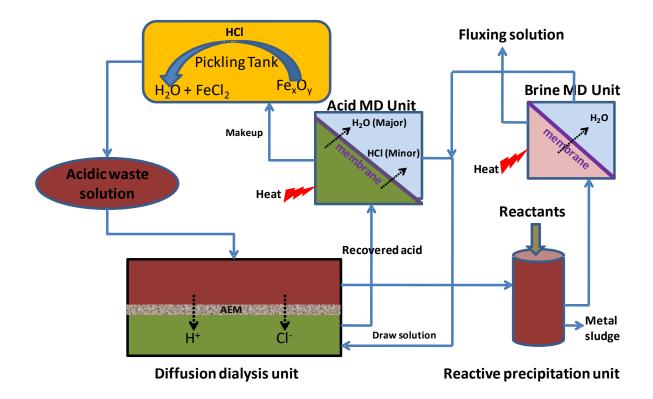


Fig.S2. Conceptual representation of Process Flow Diagram (PFD) of the membrane-integrated process for the recoveries HCl, water and salts from a pickling solution. Adopted from Ref. 336.



Title of the paper	Aimed	Membrane	Major	Ref
	application/s	composition	outcome	No.
	ystem			
	studied			
Recovery of H ₂ SO ₄ from	H ₂ SO ₄	Selemion DSV	Process	1
waste acid solution by a	recovery in		found to	
diffusion dialysis method	diamond		be feasible	
	manufacturin		and	
	g process		economica	
			lly viable	
Hybrid organic-inorganic	High level	PP host with pores	Could be	2
anion-exchange pore-filled	nuclear waste	filled with polymerized	successfull	
membranes for the recovery		[(3-Acrylamidopropyl)	У	
of nitric acid from highly		trimethyl ammonium	demonstra	
acidic aqueous waste		chloride (APMAC) and	ted with	
streams		(3-	simulated	
		acryloxypropyl)trimeth	waste	
		oxysilane (APTMS)]		
Tuning the acid recovery	HCl/NaCl/Mg	4-vinylpyridine based	Performan	3
performance of poly(4-	Cl ₂	PP AEM	ce better	
vinylpyridine)-filled			than	
membranes by the			commerci	
introduction of			al	
hydrophobic groups			membrane	
			S	
Fabrication of	HCl/FeCl ₂	brominated	Process	4
asymmetrical diffusion		poly(phenylene oxide)	capacity	
dialysis membranes for		(BPPO) ultrafiltration	increased	
rapid acid recovery with		membranes with a thin	with 3	
high purity		active layer (< 1 micron	times	
		mm thick)	increase in	
			acid purity	

 Table S1. Diffusion Dialysis studies and their major outcomes.

anion exchange membrane blended with PVA for acid recovery via diffusion dialysis processmembrane prepared by sol-gel processthan commerci al DF-120 membraneOne-step fabrication of methyfthiazole- functionalized anionIronbrominated poly(2,6- (1,0 mol·L-4)UH+ and S much6functionalized anion exchange membranes for diffusion dialysisIronbrominated poly(2,6- (1,0 mol·L-1)UH+ and S (1,0 mol·L-1)6functionalized anion exchange membranes for anion exchange membranesIndustrial acid mol·L-1 HCI)(BPPO) based methyfthiazole al DF-1201anIn-situ cross-linked porous with high performance for efficient acid recoveryIndustrial acid L-1) and FeCl2 (0.2 mol·L-1)Choromethyl poltetresulfone pentamethylleithylenet imamine as a of ifuinctional agent for magnitude ifugerMembrane imagnitude ifuger inamine as ifuger7Facile surface modification improvement of diffusion dialysis performanceHC1 (1 mot (2 2 mol·L ⁻¹) pentamethyldiethylenet ifuger imamine as a ifuger improvement of diffusionS8of anion-exchangeL-1) and FeCl2 (0.2 mol·L ⁻¹)with polypyrrole improvement of diffusion improvement of diffusionNcosepta-AF modified improvement of diffusion improvement of diffusionNcosepta-AF modified improvement of diffusion improvement of diffusion8Recovery of H2SO4 from dialysisH2SO4 from an acid leach solution by solutionDF120economic evaluadi9Recovery of H2SO4 from diffusion dialysisMagnet leach sol	Imidazolium functionalized	HCl/FeCl ₂	Imidazole based	Higher S	5
recovery via diffusion dialysis processIron polishingal DF-120 membraneOnc-step fabrication of methylthiazole- functionalized anion exchange membranes for diffusion dialysisIron polishingbrominated poly(2,6- dimethyl-1,4-Ull- and S much6functionalized anion exchange membranes for diffusion dialysisIron mol L-1 (BPO) mol·L-1 HCI)(BPPO) membranes with 4- methylthiazole functional groupsmon t.1 methylthiazole functional groupsdimethyl-1,4-In-situ cross-linked porous anion exchange membranes with high performance for efficient acid recoveryIndustrial acid (0.2 mol L^-1)Chloromethyl polyethersulfone substrate using N, N, substrate using N, N, by one-pot imagnitude higherMembrane synthesisFacile surface modification of anion-exchangeHCl (1 mol L-1) and FeCl2 (0.2 mol L^-1)Ncosepta-AF modified improvement of diffusion dialysis performanceS8for anacid leach solution by diffusion dialysisL-1) and FeCl2 (0.2 mol L^-1)with polypyrroleimproved improved improved improved8facile surface modification dialysis performanceHCl (1 mol L-1) and FeCl2 (0.2 mol L^-1)Ncosepta-AF modified improvedS8facile surface modification diffusion dialysisH2SO4 from an acid leach solution by an acid leach solution by an acid leach solution by diffusion dialysisDF120economic evaluation9	anion exchange membrane		membrane prepared by	than	
dialysis processIronbrominatedpol(2,6:UH*Membrane6One-step fabrication of methylthiazole-Ironbrominatedpol(2,6:UH*M5functionalizedanionwaste solutionphenyleneoxide)highermuch1functionalizedanionwaste solutionphenyleneoxide)highermuch1diffusion dialysisFeCl2 + 0.2membranes with 4:commercial DF-120methylthiazoleal DF-1201In-situ cross-linked porousIndustrial acidChloromethylMembrane7anion exchange membraneswater withpolyethersulfonesynthesiswith high performance for efficient acid recoveryHC1 (1 mot)substrate using N, N, pentamethyldiethylenetby one-potfunctional agent for a anion-exchangeHC1 (1 mot)Neosepta-AF modifiedNfacile surface modification of a naion-exchangeHC1 (1 mot)Neosepta-AF modifiedSfor a anion-exchangeHC1 (1 mot)Neosepta-AF modifiedS8functional agent for improvement of diffusion dialysis performanceIC1 (1 mot)Neosepta-AF modifiedS8functional a acid leach solution bi diffusion dialysisHC1 (1 mot)Neosepta-AF modifiedS8functional a acid leach solution bi diffusion dialysisHC1 (1 mot)Neosepta-AF modifiedS8functional a acid leach solution bi diffusion dialysisH2SO4 fromDF120with<	blended with PVA for acid		sol-gel process	commerci	
One-step fabrication of methylthiazole- functionalized anion waste solutionbrominated poly(2,6- dimethyl-1,4-U ^{II+} and S much6functionalized anion exchange membranes for diffusion dialysis(1.0 mol·L-1 FeCl2 + 0.2(BPPO) based membranes with 4- functional groupsthan commerci al DF-120In-situ cross-linked porous anion exchange membranesIndustrial acid HCI (1 mol L-1 and FeCl2 N', N", N"-Membrane synthesis7 synthesisefficient acid recovery efficient acid recoveryL ⁻¹) and FeCl2 N', N'', N'', N''-Membrad methyldiethylenet7 synthesisfacile surface modification dialysis performanceHCI (1 mol Nsubstrate using N, N, by one-pot pentamethyldiethylenetmagnitude riamine as a of sinfunctional agent for quaternizationmagnitude thanfacile surface modification dialysis performanceHCI (1 mol NNeosepta-AF modifiedS8facile surface modification dialysis performanceHCI (1 mol NNeosepta-AF modifiedS8of anion-exchangeHCI (1 mol NNeosepta-AF modifiedS8facile surface modification dialysis performanceHCI (1 mol NNeosepta-AF modifiedS8of anion-exchangeHCI (1 mol NNeosepta-AF modifiedS88of anion-exchangeL ⁻¹) and FeCl2 Nwith polypyrroleimprovedmembraneof anion-exchangeHCI (1 mol NNeosepta-AF modifiedS8of anion-exchangeL ⁻¹)	recovery via diffusion			al DF-120	
methylthiazole- functionalized anion exchange membranes for diffusion dialysispolishing waste solutiondimethyl-1,4- phenylene oxide)much higherdiffusion dialysis $FeCl_2 + 0.2$ mol·L ⁻¹ HCI)membranes with 4- methylthiazole functional groupscommerci al DF-120In-situ cross-linked porous anion exchange membranesIndustrial acid Water withChloromethyl polyethersulfoneMembrane synthesisinficient acid recoveryHCl (1 mol (0.2 mol L ⁻¹)substrate using N, N polyethersulfoneby one-pot magnitudeefficient acid recoveryL ⁻¹) and FeCl2 (0.2 mol L ⁻¹)N', N", N"- pentamethyldiethylentmagnitude two orders riamine as a of bifunctional agent for uaternizationMigher than than commerci al DF-120Facile surface modification of anion-exchange membranes for dialysis performanceHCl (1 mol (0.2 mol L ⁻¹)Neosepta-AF modified than commerci al DF-120SFacile surface modification dialysis performanceHCl (1 mol (0.2 mol L ⁻¹)Neosepta-AF modified than commerci al DF-120SFacile surface modification dialysis performanceHCl (1 mol (0.2 mol L ⁻¹)Neosepta-AF modified to membranesSfunctional spentor membranes for improvement of diffusion dialysis performanceH2SO4 from an acid leach solution by an acid leach solution by solutionDF120economic evaluation	dialysis process			membrane	
functionalized exchange membranes for exchange membranes for diffusion dialysiswaste solution $(1.0 mol \cdot L-1)$ $(BPPO)$ based membranes with 4- membranes with 4- methylthiazole functional groupshigher than al DF-120In-situ cross-linked porous anion exchange membranesIndustrial acid water with $(1.0 mol \cdot L^{-1} HCI)$ Choromethyl polyethersulfoneMembrane synthesis7In-situ cross-linked porous anion exchange membranesIndustrial acid water with $(0.2 mol L^{-1})$ Choromethyl synthesisMembrane polyethersulfone7efficient acid recovery efficient acid recoveryL ⁻¹) and FeCl2 $(0.2 mol L^{-1})$ N', N", N"- pentamethyldiethylenetmembrane two orders7Facile surface modification of anion-exchangeHCl (1 mol L^{-1} and FeCl2 L^{-1} and FeCl2Nichosepta-AF modified with pigher triamine as a uqaternizationS8for anion-exchange membranesHCl (1 mol L^{-1} and FeCl2 L^{-1} and FeCl2with polypyrroleimproved improved with polypyrrole8for anion-exchange membranesHCl (1 mol L^{-1} and FeCl2 L^{-1} and FeCl2with polypyrroleimproved improved improved8facile surface modification dialysis performanceHCl (1 mol L^{-1} and FeCl2 L^{-1} and FeCl2with polypyrroleimproved improved8facile surface modification dialysis performanceHCl (1 mol L^{-1} and FeCl2 L^{-1} and FeCl2with polypyrroleimproved improved8facile surface modification diffusion <b< td=""><td>One-step fabrication of</td><td>Iron</td><td>brominated poly(2,6-</td><td>$U^{H+} \mbox{ and } S$</td><td>6</td></b<>	One-step fabrication of	Iron	brominated poly(2,6-	$U^{H+} \mbox{ and } S$	6
exchange membranes for diffusion dialysis (1.0 mol·L-1) FeCl2 + 0.2 mol·L ⁻¹ HCl)(BPPO) membranes with 4- methylthiazole functional groupsthan commerci al DF-120In-situ cross-linked porous anion exchange membranes with high performance for efficient acid recoveryIndustrial acid HCl (1 mol L ⁻¹) and FeCl2 N', N", N", N"- pentamethyldiethylenet riamine as a bifunctional agent for rows-linking and bifunctional agent for quaternizationMembrane synthesis two orders ifmer al DF-120Facile surface modification of anion-exchangeHCl (1 mol L ⁻¹) and FeCl2 N', N", N", N"- method S pentamethyldiethylenet two orders riamine as a quaternizationS8Facile surface modification dialysis performanceHCl (1 mol L ⁻¹) and FeCl2 NC, N', N'', N'', N''Neosepta-AF modified with polypyrroleS8Recovery of H2SO4 from al acid leach solution by diffusion dialysisH2SO4 from an acid leach solutionDF120Cconomic pistine membranes9	methylthiazole-	polishing	dimethyl-1,4-	much	
diffusion dialysis $FeCl_2 + 0.2$ mol·L ⁻¹ HCl)membranes with 4- methylthiazole functional groupscommerci al DF-120In-situ cross-linked porous anion exchange membranesIndustrial acid water with polyethersulfoneChloromethyl substrate using N, N, by one-pot efficient acid recoveryMembrane L^{-1} and FeCl2 L^{-1} and FeCl2 $N', N'', N''.Membranesubstrate using N, N,pentamethyldicthylenettwo orders7Facile aurface modificationofanion-exchangeHCl (1 molL^{-1} and FeCl2L^{-1} and FeCl2$	functionalized anion	waste solution	phenylene oxide)	higher	
mol·L-1 HCl)methylthiazole functional groupsal DF-120In-situ cross-linked porousIndustrial acidChloromethylMembraneanion exchange membraneswater withpolyethersulfonesynthesiswith high performance forHCl (1 molsubstrate using N, N,by one-potefficient acid recoveryL ⁻¹) and FeCl2N', N", N",method S(0.2 mol L ⁻¹)pentamethyldiethylenettwo orders(0.2 mol L ⁻¹)pentamethyldiethylenettwo orders(0.2 mol L ⁻¹)pentamethyldiethylenetmagnitude(1.1 molcross-linking andhigherinfinctional agent formagnitude(1.1 molKeosepta-AF modifiedSfacile surface modificationHCl (1 molofanion-exchange(0.2 mol L ⁻¹)improvement of diffusion(0.2 mol L ⁻¹)improvement of diffusion(0.2 mol L ⁻¹)inprovement of diffusionmembranesdialysis performanceH2SO4 fromRecovery of H2SO4 fromH2SO4 froman acid leach solution byan acid leachan acid leach solution byan acid leachan acid leach solution bysolutioninflusion dialysissolutioninflusioninacid leachinflusioninacid leachinflusioninacid leach<	exchange membranes for	(1.0 mol·L-1	(BPPO) based	than	
In-situ cross-linked porousIndustrial acidfunctional groupsMembrane7anion exchange membraneswater withpolyethersulfonesynthesis7with high performance forHCl (1 molsubstrate using N, N,by one-pot1efficient acid recoveryL ⁻¹) and FeCl2N', N", N"-method S1(0.2 mol L ⁻¹)pentamethyldiethylenettwo orders1infunctional agent formagnitudebifunctional agent formagnitudeinfusioninfusioninfusioninfusion1facile surface modificationHCl (1 molNeosepta-AF modifiedS8ofanion-exchangeL ⁻¹) and FeCl2with polypyrroleimprovedimprovedfacile surface modificationHCl (1 molNeosepta-AF modifiedS8ofanion-exchangeL ⁻¹) and FeCl2with polypyrroleimprovedimprovedimprovement of diffusionL ⁻¹) and FeCl2with polypyrroleimproved9idilysis performanceL ⁻¹) and FeCl2with polypyrroleimproved9an acid leach solution byan acid leachDF120economic9an acid leach solution byan acid leachan acid leachicutionrevealed	diffusion dialysis	$FeCl_2 + 0.2$	membranes with 4-	commerci	
In-situ cross-linked porousIndustrial acidChloromethylMembrane7anion exchange membraneswater withpolyethersulfonesynthesissynthesiswith high performance forHC1 (1 molsubstrate using N, N,by one-potefficient acid recoveryL ⁻¹) and FeCl2N', N", N"-method S(0.2 mol L ⁻¹)pentamethyldiethylenettwo orders(0.2 mol L ⁻¹)pentamethyldiethylenettwo ordersiffusion agent formagnitudehigherquaternizationthancommerciofanion-exchangeL ⁻¹) and FeCl2with polypyrroleimprovedfacile surface modificationHC1 (1 molNeosepta-AF modifiedS8ofanion-exchangeL ⁻¹) and FeCl2with polypyrroleimprovedimprovement of diffusion(0.2 mol L ⁻¹)improvedmembrane9idalysis performanceH2SO4 fromDF120economic9an acid leach solution byan acid leachsolutionrevealed		mol·L ⁻¹ HCl)	methylthiazole	al DF-120	
anion exchange membraneswater with HCl (1 molpolyethersulfonesynthesiswith high performance for efficient acid recoveryHCl (1 molsubstrate using N, N, pentamethyldiethylenetby one-pot L^{-1} and FeCl2N', N", N"-method Si.i.(0.2 mol L ⁻¹)pentamethyldiethylenettwo orders(0.2 mol L ⁻¹)pentamethyldiethylenetmagnitudeifunctional agent for quaternizationmagnitudehigherthancross-linking and quaternizationhigherfacile surface modificationHCl (1 mol L ⁻¹) and FeCl2Neosepta-AF modifiedSof anion-exchangeL ⁻¹) and FeCl2with polypyrroleimprovedmembranesfor (0.2 mol L ⁻¹)Neosepta-AF modifiedSof anion-exchangeL ⁻¹) and FeCl2with polypyrroleimprovedimprovement of diffusion dialysis performanceL ⁻¹) and FeCl2with polypyrrolepristine pristinefacecovery of H2SO4 from diffusion dialysisH2SO4 fromDF120economic9an acid leach solution by diffusion dialysisan acid leachsolutioniervealediervealed			functional groups		
with high performance for efficient acid recoveryHCl (1 mol L^{-1}) and FeCl2 $(0.2 mol L^{-1})substrate using N, N,pentamethyldiethylenetby one-potmethod S(0.2 mol L^{-1})(0.2 mol L^{-1})pentamethyldiethylenettwo orders(0.2 mol L^{-1})pentamethyldiethylenetmagnitude(0.2 mol L^{-1})quaternizationthan(0.2 mol L^{-1})Neosepta-AF modifiedS(0.2 mol L^{-1}) and FeCl2with polypyrroleimproved(0.2 mol L^{-1})Neosepta-AF modifiedS(0.2 mol L^{-1})(0.2 mol L^{-1})respect to(1 mord(0.2 mol L^{-1})pristine(1 mord(0.2 mol L^{-1})respect to(1 mord(0.2 mol L^{-1})pristine(1 mord(1 mord$	In-situ cross-linked porous	Industrial acid	Chloromethyl	Membrane	7
efficient acid recovery L^{-1} and FeCl ₂ N', N", N", N"- $(0.2 \text{ mol } L^{-1})$ and FeCl ₂ N', N", N", N"- pentamethyldiethylenet two orders riamine as a of bifunctional agent for quaternization than commerci al DF-120 Facile surface modification HCl (1 mol of anion-exchange L^{-1}) and FeCl ₂ membranes for dialysis performance (0.2 mol L^{-1}) membranes for dialysis performance H2SO4 from an acid leach solution by diffusion dialysis method S solution H2SO4 from diffusion dialysis method S solution H2SO4 from solution H2SO4 from diffusion dialysis method S solution H2SO4 from solution H2SO4 from diffusion dialysis method S solution H2SO4 from diffusion dialysis method S solution H2SO4 from H2SO4 fr	anion exchange membranes	water with	polyethersulfone	synthesis	
	with high performance for	HCl (1 mol	substrate using N, N,	by one-pot	
kriamineasofkkignerkignerbifunctional agent formagnitudecross-linkingandhigherkignerquaternizationthancommercial DF-120facile surface modificationHCl (1 molofanion-exchangeL ⁻¹) and FeCl2with polypyrrolemembranesfo(0.2 mol L ⁻¹)kignerimprovement of diffusionKenerdialysis performancevithkrespect topristinemembranenembraneshg2SQ4 froman acid leach solution byan acid leachdiffusion dialysissolutionk	efficient acid recovery	L ⁻¹) and FeCl ₂	N', N", N"-	method S	
Image: height space is a space is space i		$(0.2 \text{ mol } L^{-1})$	pentamethyldiethylenet	two orders	
Recovery of H2SO4 from an acid leach solutionHCl (1 mol H2SO4 from BasilitionNerver H2SO4 from BasilitionRecover H2SO4 from BasilitionHCl (1 mol HCl (1 mol H			riamine as a	of	
Aquaternizationthanquaternizationthancommercial DF-120al DF-120Facile surface modificationHCl (1 molNeosepta-AF modifiedSof anion-exchangeL ⁻¹) and FeCl2with polypyrroleimprovedmembranesfor(0.2 mol L ⁻¹)Feclewith polypyrroleimprovement of diffusionKFeclepristinedialysis performanceFecleDF120economicRecovery of H2SO4 fromH2SO4 fromDF120economican acid leach solution byan acid leachsolutionrevealed			bifunctional agent for	magnitude	
Image: series of the series			cross-linking and	higher	
Image: definition of an ion exchangeHCl (1 molNeosepta-AF modifiedal DF-1208of anion-exchange L^{-1} and FeCl2with polypyrroleimprovedimprovedmembranesfor $(0.2 \text{ mol } L^{-1})$ with polypyrrolewith1improvement of diffusionLLFeCl2pristine1dialysis performanceLLLpristine1Recovery of H2SO4 fromH2SO4 fromDF120economic9an acid leach solution byan acid leachsolutionrevealed1			quaternization	than	
Image: constraint of the surface modificationImage: constraint of the surface modificationImage: constraint of the surface modificationImage: constraint of the surface modifiedImage: constraint of the surfaceImage: constraint of the surface				commerci	
ofanion-exchange L^{-1} and FeCl2with polypyrroleimprovedmembranesfor $(0.2 \text{ mol } L^{-1})$ with polypyrrolewithimprovement of diffusion $(0.2 \text{ mol } L^{-1})$ respect topristinedialysis performance L^{-1} L^{-1} membranepristineRecovery of H2SO4 fromH2SO4 fromDF120economic9an acid leach solution byan acid leachsolutionrevealed1				al DF-120	
membranesfor (0.2 mol L^{-1})in the formimprovement of diffusion dialysis performance(0.2 mol L^{-1})with respect to pristine membraneRecovery of H2SO4 from an acid leach solution by diffusion dialysisH_2SO_4 from an acid leach solutionDF120economic evaluation revealed	Facile surface modification	HCl (1 mol	Neosepta-AF modified	S	8
$ \begin{array}{c} \mbox{improvement of diffusion} \\ \mbox{dialysis performance} & & & & & & & & & & & & & & & & & & &$	of anion-exchange	L ⁻¹) and FeCl ₂	with polypyrrole	improved	
dialysis performancepristinedialysis performancepristineRecovery of H2SO4 from H_2SO_4 fromDF120economican acid leach solution byan acid leachdiffusion dialysissolution	membranes for	$(0.2 \text{ mol } L^{-1})$		with	
Recovery of H2SO4 from an acid leach solution by diffusion dialysisH2SO4 from an acid leach solutionDF120economic evaluation revealed9	improvement of diffusion			respect to	
Recovery of H2SO4 fromH2SO4 fromDF120economic9an acid leach solution by diffusion dialysisan acid leachevaluationrevealed	dialysis performance			pristine	
an acid leach solution by diffusion dialysisan acid leach solutionevaluation revealed				membrane	
diffusion dialysis solution revealed	Recovery of H2SO4 from	H ₂ SO ₄ from	DF120	economic	9
	an acid leach solution by	an acid leach		evaluation	
produced that an	diffusion dialysis	solution		revealed	
produced inat an		produced		that an	

	during the		investment	
	vanadium		in this	
	manufacturin		process	
	g process		could be	
	01		recovered	
			within 27	
			months	
Recovery of hydrochloric	HCl/FeCl ₂ /Zn	DF120	Leakage	10
acid from the waste acid	Cl_2		of other	
solution by diffusion			salts	
dialysis			observed	
Separation and recovery of	H ₂ SO ₄ from	DF120	Efficient	11
sulfuric acid from acidic	an acid leach		rejection	
vanadium leaching solution	solution		of V, Al	
by diffusion dialysis	produced		and Fe	
	during the		ions wrt H	
	vanadium		could be	
	manufacturin		shown	
	g process			
Poly (triethoxyvinylsilane-	HCl/FeCl ₂	triethoxyvinylsilane	Reduction	12
со-		and quaternized vinyl	in swelling	
quaternaryvinylbenzylchlor		benzyl chloride based	ratio and	
ide)/fGNR based anion		AEM modified with	improvem	
exchange membrane and its		functionalized	ent in IEC	
application towards salt and		graphene nano-ribbons	due to	
acid recovery		(fGNR)	functionali	
			zed	
			graphene	
			nano-	
			ribbons	
			(fGNR)	
			presence	

Covalently cross-linked	HCl/FeCl ₂	covalently cross-linked	performan	13
pyridinium based AEMs		pyridinium based	ce better	15
with aromatic pendant		AEMs	than	
1		ALMS		
groups for acid recovery via			commerci	
diffusion dialysis			al	
			membrane	
			S	
The recovery of sulphuric	Recovery of	DF120	DD found	14
acid from the waste anodic	H_2SO_4 from		to be cost	
aluminum oxidation	waste anodic		effective	
solution by diffusion	aluminum			
dialysis	oxidation			
	solution			
Recovery of hydrochloric	HCl from	spiral wound diffusion	Investmen	15
acid from simulated	simulated	dialysis (SWDD)	t could be	
chemosynthesis aluminum	chemosynthes	membrane	recovered	
foil wastewater by spiral	is aluminum		within	
wound diffusion dialysis	foil		16.5	
(SWDD) membrane	wastewater		months	
module	wastewater		montils	
Effective recovery of acids		egg shell membrane	egg shell	16
		powder loaded on	membrane	10
		•		
1		polysulfone membrane	powder	
membranes: A step towards			enhances	
sustainable development			proton	
			permeabili	
			ty of	
			polysulfon	
			e	
			membrane	
Diffusion dialysis		semi-interpenetrating	performan	17
membranes with semi-		networks in polyvinyl	ce better	
interpenetrating network		chloride (PVC)	than	

for acid recovery			commerci	
·			al	
			membrane	
			s	
Advanced charged porous		Porous brominated	performan	18
membranes with ultrahigh	HCl/FeCl ₂ /Al	poly(2,6-dimethyl-1,4-	ce better	10
_				
selectivity and permeability	Cl ₃	phenylene oxide)	than .	
for acid recovery		(BPPO) membranes	commerci	
			al	
			membrane	
			S	
Anion exchange	acid from	quaternized poly(2,6-	Membrane	19
membranes used in	organic	dimethyl-1,4-	s less	
diffusion dialysis for acid	solution	phenylene oxide)	erosive	
recovery from erosive and	containing	(QPPO) and polyvinyl	and	
organic solutions	HC1 and	alcohol (PVA)	performan	
	glyphosate		ce better	
			than	
			commerci	
			al	
			membrane	
Graphene oxide embedded	HCl/FeCl ₂	Three phase graphene	Improved	20
"three-phase" membrane to	_	oxide sheet based	efficiency	
beat "trade-off" in acid		AEMs	and	
recovery			separation	
Anion exchange	HCl/FeCl ₂	quaternized poly(2,6-	Performan	21
membranes from hot-		dimethyl-1,4-	ce better	~ 1
pressed electrospun QPPO-		phenylene	than	
		1 2		
SiO2 hybrid nanofibers for		oxide)/Silicon dioxide	commerci	
acid recovery		hybrid material	al	
			membrane	
			S	
Porous diffusion dialysis	HCl/FeCl ₂	brominated poly	Performan	22

recovery(BPPO) ultrafiltration membranethan commerci al membranePorousBPPO-based membraneHCl/FcCl2triphenylamine based porous (AEM with brominated poly(2,6- dimethyl-1,4- to phenylencoxide)Performan comprable dimethyl-1,4- to phenylencoxide)23Novel quaternized aromatic amine based hybrid PVA membranes for acid recoveryHCl/FeCl2 membranequaternized 4,40 - (1,10 phenylencoxide)Performan commerci al membrane24Asymmetrically porousHCl/FeCl2 membranesquaternized anomatic diyldioxyldianiline alcohol (PVA) based al AEMebiphenyl-4,40 membranece better alcohol (PVA) based al al AEMperforman s24Asymmetrically porousHCl/FeCl2 HCl/FeCl2Asymmetric alcohol (PVA) based al alcohol (PVA) based al al al al al membrane25Improved acid recoveryHCl/FeCl2 membranesAsymmetric al al al al al al membrane25Asymmetrically porousHCl/FeCl2 membrane al al al al al al membrane26performance by novel poly(DMAEM-co-γ-MPS) anion exchange membraneHCl/FeCl2 membrane polymerizationNovel membranes than than than than26performance poly(DMAEM-co-γ-MPS) anion exchange membraneHCl/FeCl2 membrane polymerizationNovel membranes than commerci than commerci26	membranes for rapid acid		(phenylene oxide)	ce better	
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via diffusion dialysis al	anion exchange membrane			commerci	
	via diffusion dialysis			al	

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Recovery of sulfuric acid	sulfuric acid	DF-120-III	Process	27
from a stone coal acid	from a stone		found to	
leaching solution by	coal acid		be feasible	
diffusion dialysis	leaching			
	solution			
Investigation of key process	HCl/FeCl ₂	methyl 6-	Process	28
parameters in acid recovery		(dimethylamino)	parameters	
for diffusion dialysis using		hexanoate (MDMH)	studied	
novel (MDMH-QPPO)		and poly (2, 5-	using full	
anion exchange membranes		dimethylphenyl oxide)	factorial	
		based AEM	design	
Quaternized poly(2,6-	HCl/FeCl ₂	quaternized poly(2,6-		29
dimethyl-1,4-phenylene		dimethyl-1,4-	Introducti	
oxide)s with zwitterion		phenylene oxide)s	on of	
groups as diffusion dialysis		(PPO) anion exchange	zwitterioni	
membranes for acid		membranes (AEMs)	c groups	
recovery			into anion	
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			simultaneo	
			usly	
			improves	
			dialysis	
			coefficient	
			and	
			selectivity	
Supplementing multi-	HCl/FeCl ₂	plant waste	Performan	30
functional groups to		(Azadirachta indica,	ce better	
polysulfone membranes		neem leaves powder	than	
using Azadirachta indica		(NP)) as filler to	commerci	
leaves powder for effective		polysulfone (PSf)	al	

and highly selective acid		membrane	membrane	
recovery			S	
In-situ crosslinked AEMs with self-assembled nanostructure for acid recovery	HCl/FeCl ₂	tris(2-(2- methoxyethoxy) ethyl) amine (TDA) functionalized bromo poly(2, 6-dimethyl-1, 4 phenylene oxide)	Membrane s exhibited better operationa 1 stability for 10 consecutiv e cycles during the entire diffusion dialysis process.	31
High proton selectivity membrane based on the keto-linked cationic covalent organic framework for acid recovery	HCl/FeCl ₂	keto-linked covalent organic frameworks with high acid-stability was fabricated on the surface of carboxyl- modified polyacrylonitrile (CPAN) ultrafiltration membrane	ce after 10	32
Fabricationandcharacterizationofpyridiniumfunctionalizedanionexchangeforacidrecovery	HCl/FeCl ₂	brominated poly (2,6- dimethyl-1,4- phenylene oxide) (BPPO) as a polymer backbone and 4- methylpyridine (MP) based AEM	Performan ce better than commerci al membrane s	33

Construction of two	HCl/FeCl ₂	2D AEMs were	High	34
dimensional anion		fabricated by layer by	separation	
exchange membranes to		layer stacking the	performan	
boost acid recovery		graphene oxide	ce after 10	
performances		nanosheets decorated	cycle	
		by imidazolium cations		
		(Im-GO)		
Acid-triggered polyether	H ₂ SO ₄	PES (polyether sulfone)	Permeabili	35
sulfone - Polyvinyl	recovery from	- PVP (polyvinyl	ty	
pyrrolidone blend anion	titania waste	pyrrolidone) blend	coefficient	
exchange membranes for		membranes	s remain	
the recovery of titania waste			unchanged	
acid via diffusion dialysis			for 337	
			days	
Prepared poly(aryl	HCl/FeCl ₂	self-organized	Performan	36
piperidinium) anion		nanostructured cross-	ce better	
exchange membranes for		linked AEMs based on	than	
acid recovery to improve		poly (aryl piperidinium)	commerci	
dialysis coefficients and			al	
selectivity			membrane	
			s	
Polysulfone/graphene	HCl/FeCl ₂	chloromethylated	shows	37
quantum dots composite		polysulfone membranes	potential	
anion exchange membrane		are prepared with	for acid	
for acid recovery by		different concentrations	recovery	
diffusion dialysis		of graphene quantum		
		dots		
Novel poly (ionic liquid)-	HCl/FeCl ₂	poly (ionic liquids)-	Performan	38
based anion exchange		based AEMs by the free	ce better	
membranes for efficient and		radical polymerization	than	
rapid acid recovery from		of 1-butyl-3- vinyl	commerci	
industrial waste		imidazolium bromide,	al	
		acrylic acid, styrene,	membrane	

Influence of hydrophobic components tuning of poly (aryl ether sulfone)s ionomers based anion diffusion dialysis for acid recoveryHCl/FeCl2 v hanquaternized poly(arylene ether sulfone)sPerforman ce better al membrane membrane39 ce better al membraneHigh-performance porous anion exchange membranes for efficient acid recoveryHCl/FeCl2 v hanporous brominated poly (phenylene oxide) al membranePerforman ce better membrane40 ce better membranefrom acidic wastewater by diffusion dialysisHCl/FeCl2 v v hanquaternized poly(henylene poly(hiphenyl based AEMsPerforman commerci al membrane41 ce better hanfrom acidic wastewater by diffusion dialysisHCl/FeCl2 v v to acid recoveryquaternized poly(hiphenyl based AEMsPerforman ce better inembrane41 ce better piperidine) polymers poly(hiphenyl based AEMsPerforman ce better inamefor acid recoveryHCl/FeCl2 v poly(arylene on poly(aryleneAEMs commerci al al41 ce better piperidine) poly(arylene piperidinium) with bis- cation strings for diffusion diffusion diffusion diffusion42 ce better piperidinium) with bis- cation strings for diffusion diffusion diffusion diffusion diffusion42 ce better piperidinium) with bis- cation stringscommerci cation strings42 commerci cation stringsNanostructured on poly(arylene on poly(aryleneHCl/FeCl2 cation stringsAEMs commerci cation stringscommerci cation strings <th></th> <th></th> <th>and acrylonitrile under</th> <th>S</th> <th></th>			and acrylonitrile under	S	
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from acidic wastewater by diffusion dialysis biffusion dialysis Enhanced diffusion dialysis performance of cross- linked poly(aryl piperidine) anion exchange membranes by thiol-ene click chemistry for acid recovery Nanostructured anion exchange membranes based on poly(arylene piperidinium) with bis- cation strings for diffusion dialysis in acid recovery	anion exchange membranes		(phenylene oxide)	ce better	
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anion exchange membranes by thiol-ene click chemistry for acid recoverybased AEMscommerci al membranefor acid recoverynembrane csNanostructured exchange membranes basedHCl/FeCl2AEMs poly(arylenePerforman ce betteron poly(arylene piperidinium) with bis- cation strings for diffusion dialysis in acid recoveryHCl/FeCl2AEMs poly(arylene piperidinium) with bis- cation stringsDerforman cation strings42al membranen piperidinium) membraneal membrane1	performance of cross-		poly(biphenyl	ce better	
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onpoly(arylenepiperidinium) with bis-thanpiperidinium) with bis-cation stringscommercication strings for diffusionalaldialysis in acid recoverymembrane	Nanostructured anion	HCl/FeCl ₂	AEMs based on	Performan	42
piperidinium) with bis- cation strings for diffusion dialysis in acid recoverycation stringscommerci al membrane	exchange membranes based		poly(arylene	ce better	
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	cation strings for diffusion			al	
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				s	

Internally cross-linked poly	HCl, HNO ₃ ,	internally crosslinked	Performan	43
(2,6-dimethyl-1,4-	H_2SO_4	poly (2,6-dimethyl-1,4-	ce better	
phenylene ether) based		phenylene ether) (PPE)	than	
anion exchange membrane		based AEMs	commerci	
for recovery of different			al	
acids by diffusion dialysis			membrane	
			S	
Cationic covalent organic	HCl/FeCl ₂	acid-stable cationic	High	44
framework membranes		COF (DhaTGCl) layers	separation	
with stable proton transfer		with intralayer	performan	
channel for acid recovery		hydrogen bond on the	ce after 10	
		surface of hydrolytic	cycle	
		polyacrylonitrile		
		(HPAN) ultrafiltration		
		membrane		
Piperazine-functionalized	HCl/FeCl ₂	porous chloromethyl	Long term	45
porous anion exchange		polyethersulfone	excellent	
membranes for efficient		(CMPES) membrane	thermal	
acid recovery by diffusion		modified by 1,4-	stability	
dialysis		dimethylpiperazine	and acid	
		(DMP)	resistance	
Investigation on flexible	HCl/FeCl ₂	Cross-linked	High	46
and thermally crosslinked		membranes prepared	dialysis	
bis-piperidinium-PPO		using phase di-cationic	coefficient	
anion exchange membrane		cross-linking strategy	and	
(AEM) for electro-kinetic			separation	
desalination and acid			factor	
recovery				
GO-anchored imidazolium	HCl/FeCl ₂	graphene oxide (GO)	High	47
based cross-linked		into N-alkylated	dialysis	
composite anion exchange		polyacrylonitrile-co-	coefficient	
membranes for the		polyvinyl imidazole	and	
enhancement in acid		copolymer based AEMs	separation	

recovery via diffusion dialysis			factor	
EngineeringrobustRGO/PVAcompositemembrane for acid recoveryviaelectronirradiation	HCl/FeCl ₂	graphene oxide (GO) and polyvinyl alcohol (PVA) based membranes	Performan ce comparabl e to commerci al membrane s	48
Crosslinking imidazolium- intercalated GO membrane for acid recovery from low concentration solution	HCl/FeCl ₂	crosslinked imidazolium intercalated GO membrane	Recovery feasible with the synthesize d membrane s	49
Constructing proton selective pathways using MOFs to enhance acid recovery efficiency of anion exchange membranes	HCl/FeCl ₂	AEMs based on metalorganic frameworks	Recovery feasible with the synthesize d membrane s	50
Chemically stable and high acid recovery anion exchange membrane	HCl/FeCl ₂	N-methyl-4-piperidone (NMPi) based thermoset AEMs	Recovery feasible with the synthesize d membrane s	51

Table S2. The advantages and	'disadvantages of the standalone remediation and recycling
methods.	

Technology	Method	Advantages	Disadvantages
Remediation method	Neutralization and Precipitation	Simple and inexpensive, suited for low acidity aqueous waste, large volume can be treated	Insufficient for zero waste discharge due to presence of toxic metal ions, slow precipitation and sedimentation, formation of watery sludge or secondary waste
	Pyrohydrolysis	Specific to spent pickle liquor or similar type of aqueous waste	Insufficient for zero waste discharge, energy intensive, generation off toxic gases, secondary waste formation
	Thermal decomposition/ bio-denitrification	Simple and very effective method, suited for low acidity and low volume.	Insufficient for zero waste discharge, Possibility of significant amount of energy consumption, generation of toxic gases, secondary waste formation, and large volume treatment of aqueous waste is not feasible.
	Coagulation and flocculation	Simple, economical and does not require separate unit, often coupled with precipitation.	Secondary waste generation, incomplete metal ions removal, may need pH control to remove metal ions.
	Crystallization	Crystallization is an effective way to get rid of ferrous chloride in water after hydrochloric acid pickling.	The crystallization requires considerable energy, it is challenging to remove from the waste acids strong metallic ions like Fe ions, there isn't a economically viable way to handle the crystal that was removed.
Regeneration method	Solvent extraction	Acid can be selectively removes with appropriate extractant	Requires special plants, high purity acid may not be achieved, capital intensive, does not suit to low water consumption and zero waste discharge.
	Ion-exchange	Selective for ions removal, large volume can be processes	High purity acid not recovered, large volume of aqueous waste may generate, does not suit to low water consumption and zero waste discharge
Membrane technology	Nanofiltration and Reverse	High purity water can be obtained from RO,	RO may be suited for concentrating aqueous waste

Osmosis	NF can separate acid from multivalent metal ions. Process is faster than any other membrane	not acid recovery, NF membranes are not stable in high acidic condition, and high purity acid is not recovered. Zero waste discharge not possible due to the presence of metal ions in the rejected water.
Membrane Distillation	Well suited for recovery of high purity water from acidic waste, low waste heat utilization	HCl can vaporize and pass through membrane with water, not suited for recovery of acid from the waste.
Diffusion dialysis	High purity acid can be recovered and recycled, low energy consumption, economical and simple	Process is slow and only 50% acid from feed can be recovered.
Electrodialysis	With monovalent selective membrane, electrodialysis can separate acid from aqueous waste	Well suited for the salt removal, and H ⁺ -ions selective cation exchange membrane is required, proton leakage through anion-exchange membrane is problem, and reverse flow of water is also problem, if concentration difference is higher between two compartments separated by the membrane.

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