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Technologies for the wastewater circular economy – A review

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ABSTRACT

Throughout the years, experiments with membrane, electrochemical, biological and thermal technologies have been explored to recover resources from a range of wastewaters such as municipal, industrial, urine and sewage sludge. However, multiple resource recoveries at the commercial and pilot scale are still lacking, instead, focusing on specialising on the recovery of a narrow set of products. Herein, a divergence of resource recovery across municipal and industrial wastewater streams – nutrients and energy for municipal; heavy metals and water recovery for industrial streams; with material recovery seen across both – was observed through literature review. This review aims to provide a perspective for academic and professionals alike on the current technologies available and their emerging trends – and aims to tie in these technologies to wastewater circular economics. Consequently, high sludge and wastewater transportation costs may pressure wastewater treatment plants (WWTPs) to adopt value-adding, resource recovery technologies onsite – transforming centralised and decentralised WWTPs into wastewater resources recovery facilities.

1. Introduction

Wastewater is being generated at an exponential rate proportional to the rise in the world's populations to suffice endless economic growth under the constraints of finite resources. Approximately 80% of the world's wastewater is discharged into the environment without adequate treatment, and only 8% of industrial wastewater is treated in developing countries [1]. According to the European Investment Bank, each year around 380 billion m^3 of wastewater is produced and this is set to increase at a rate of 24% by 2030 and 51% by 2050 [2]. The amount of wastewater that is treated varies depending on the developing-developed status of nations – where high income countries treat around 70% of wastewater with 28% for developing economies [2]. About 70% of the world's water is also used for irrigation and agricultural purposes, followed by 16% for industrial wastewater and 8% for municipal [2,3].

Wastewater can serve as a valuable source for resource recovery, incorporating nutrients, energy, water and materials. Phosphorous is expected to run out within the next 50 to 100 years, and recovering phosphorous through wastewater could meet 22% of the world's demand, with existing systems such as the Ostara Nutrient Recovery Technologies used by Stickney wastewater treatment plant (WWTP) which is already achieving recovery rates of up to 85% [3]. Wastewater is also energetic in value, with biogases and chemical energy recovery rates of ~80% and ~20% respectively [3]. Meanwhile, industrial wastewater is rich in precious metals such as gold, silver, copper and platinum [4]. The primary barriers to nutrient and energy recoveries from wastewater are the lack of profitability, invested infrastructures in place, inadequate policies in place to facilitate circular economy (CE) in treatment plants, and the emerging technologies are yet to reach the market [3], with potential from the recovery of heat and nutrients reaching 25% of the current market demand [5]. A large percentage of water consumed is used for irrigation and farming purposes, and approaches such as hydroponics to cut down water consumption [6] and simultaneous water-nutrient recoveries are explored [7]. Wastewater as a resource can recover biofuels, biogases, biochar, biofertilisers, biooils,

Abbreviations: AD, Anaerobic Digestion; AnMBR, Anaerobic Membrane Bioreactor; API, Active Pharmaceutical Ingredient; BMED, Bipolar Membrane Electrodialysis; CC, Chemical Coagulation; CDI, Capacitive Deionisation; CE, Circular Economy; DOC, Dissolved Oxygen Content; DS, Draw Solute; EC, Electrocoagulation; ED, Electrodialysis; ES, Electrosorption; FS, Feed Solute; FC, , Freeze Concentration; FO, Forward Osmosis; GHG, Greenhouse Gas; GPM, Gas Permeable Membrane; HRT, Hydraulic Retention Time; HTC, Hydrothermal Carbonisation; HTL, Hydrothermal Liquefaction; HTT, Hydrothermal Treatment; IXM, Ion Exchange Membrane; MBR, Membrane Bioreactor; MD, Membrane Distillation; MEC, Microbial Electrolysis Cell; MFC, Microbial Fuel cell; PRO, Pressure Retarded Osmosis; RED, Reverse Electrodialysis; RO, Reverse Osmosis; RSF, Reverse Salt Flux; WWTP, Wastewater Treatment Plant

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and bioplastics, however, cost recoveries are higher for resource recovery than it is for pure discharging [8]. Recovered products on the other hand have marketable values that can be resold for profits to offset recovery costs and potentially breakeven towards profits. Cost barriers disincentivise WWTP operators from adopting resource recovery technologies. Table 1 shows the various studies that were done to recover multiple types of products across industrial and municipal wastewater streams for pilot plants.

Wastewater resource recovery disciplines are clearly divided along municipal (household, livestock and pulp mills) and industrial waste streams, given these streams are separated, such approaches can isolate recovery technologies from one another. Review papers also sought to examine membrane [9], bioelectrochemical (microbial fuel cells, microbial electrolysis and microbial desalination) [10], microalgae and algal [11,12] from resource recovery lenses, however, little overlap in the benefits across these technologies can be used in conjunction with other waste streams. For example, electrochemical deposition methods for P-recovery in industrial [13] versus municipal wastewater [14] is an example of how electrochemical technologies can be used to recover resources across a range of wastewater influents. Other resource recovery review papers for wastewater also attempt to unify the disciplines by focusing on the range of technologies [15], products recoverable and flows [4,16], economic returns [5], energy feasibility [10], environmental benefits [17], climate impacts [18] and implementation [17].

This review paper aims to highlight the strengths, weaknesses and overlaps that each of the CE WWTP technologies have across municipal and industrial wastewater. Nexus CE WWTP papers draw on the relationships from several angles including nutrient, water, mineral and energy recoveries [19–22] – establishing relationships between land, water and agriculture. These papers cover economic benefits, environmental benefits, energy benefits, and process benefits. However, what these papers lack are the cross-sector benefits of adopting CE WWTP at the component, resource, and operating level and the versatility of the recovered products that can be applied across industrial and municipal WWTPs. For example, the recovery of heavy metals as micronutrients for CE fertilisers, producing electrodes from sewage-derived hydrothermal carbon and precious metals, reconcentrating nutrients with membrane processes for microalgae cultivation to produce nutraceuticals and bioplastics, CE WWTP-derived microalgae biomass production of calcium carbonate to construct WWTPs, and so on. These technologies are then evaluated from a process-to-applications perspective to help the reader appreciate a fully circular WWTP.

2. Trends in resource recovery from wastewater

2.1. Urine

Urine contains a large concentration of nitrogen, phosphorus and potassium. Most studies apply membrane and biological methods to recovering nutrients from this waste stream (Table 2) where nutrient rejection and concentration yields can reach > 99%. The incorporation of microbial fuel cells (MFCs) that require no external power sources to nutrients was experimented in Freguia et al. [42] and Gao et al. [43]. Microalgae can also be grown in urine [44–48] for N and P recoveries but are slowed by fouling [44] and its performance is dependent on sunlight and concentrations of urine [49].

Urine is also an excellent catalyst for microbial electrolysis cell (MEC) [50–52], and MECs can oxidise antimicrobial resistant active pharmaceutical ingredients (APIs) in urine [53,53] and inhibit microbial activity [54,55]. Treated urine can then be used asa safe N-P-K fertiliser for CE applications [55]. Recoveries of hydrogen [56,57], ammonia [58], nitrogen [59], and phosphorous [60,61] could be done, however, due to the lack of source-separation infrastructure, much of this urine is diluted – making it inefficient for nutrient CE [62]. Ideally, nutrient recoveries should be done on pure urine which is around 5.3 times more efficient than diluted flushed urine [63].

By capturing and treating undiluted urine at the source, this would reduce treatment loads on conventional WWTPs while achieving higher nutrient recovery efficiencies. Membrane technologies by far, show great potential for concentrating the volume of urine into a highly valuable, nutritious waste taking up less space for efficient transportation while recovering water. This waste can then be further processed efficiently by other technologies such as electrochemical precipitation or be used as microalgae feedstock. In most cases, this recovered urine is converted directly into a fertiliser to close the nutrient loop. Additionally, there appears to be a trade-off between recoverable nutrients and power generation, as microbial activity at the electrode surface consumes nutrients to produce the bioelectrochemical power needed.

2.2. Sewage sludge

Anaerobic digestion (AD) is a mature and commonly used technology to process sewage sludge for resource recovery (Table 3). Methane, hydrogen, volatile fatty acids, hydrochar and nutrient/compost production [97,98,99] are some products that can be recovered. Co-digestion is one of the most effective CE methods for recovering nutrients and biogas from sewage sludge, given substrates can be introduced to activate the sludge, bring microbial diversity, provide greater buffer and dilute dangerous metal substances [100–103]. However, sewage AD suffers from issues removing heavy metal contaminants, pathogens, microplastics, APIs, and other pollutants [104], and its methane yield is dependent on lipid quantities [103]. Ultrasonication and fermentation can be proposed as a method of removing heavy metals [105].

Across the EU, sewage sludge landfilling makes up about 11% of the total sewage treatment process and this is being phased out [106]. 40% of the 2 to 3 million tonnes of sewage sludge each year is applied directly on farmlands – representing the most common method of managing sewage waste. However, this practice comes with pathogenic risks and human exposure to active pharmaceuticals and toxins. Incineration methods make up 27% of sewage treatment in the EU, contrarily, these thermal approaches emit significant amounts of carbon to produce biochar, biofuels, biomaterials, biogases, biomasses and nutrients for the high amounts of energy inputted. It is one of several avenues to reducing sewage landfilling and producing soil conditioners and biofertilisers that are safer for crop yielding compared to direct applications.

2.3. Municipal wastewater

In Table 4, a more interesting trend in the resource recovery of municipal wastewaters is the use of microalgae [107,135]. However, one of the most cost intensive parts of biofuel conversion is the consumption on N-P-K nutrients – which is 20–30% of the total to sustain the microalgae [136,137] and the harvesting of biomass [138–140], although, electrocoagulation [141] and microalgal-bacterial aggregates [142] were proposed as a method of overcoming the latter. To circumvent intense nutrient consumption, wastewater or recycling excess nutrients were proposed [143,144]. The use of microalgae for the circular bioeconomy could recover nutrients from algal biomasses [145,146], lower energy consumption for managing wastewater [147,148] and could benefit vertical farming hydroponic systems [87]. Nutrients and CO_2 are captured by the microalgae, producing biofuels during the consumption of sugars, and production of fertilisers with the wastewater upcycled into a valuable nutritious effluent [145,149,150] - in fact, C, N, P, S and other metals are all essential macronutrients for microalgae to thrive [151]. Therefore, nutrient recovery requires direct application of microalgae biomasses as biosolid fertilisers [152–154].

The use of MFCs for municipal wastewater is another fascinating area of research through combined use of microorganisms and electrochemical methods, but challenges remain to remove, recover and

Table 1
Overview of wastewater recovery pilot plant technologies focusing on resource recovery.

Technology	Waste Type	Challenges	Solutions	Nutrient	Energy	Water	Metals/Materials	Source
AD + Microalgae + Membrane Contactor	Sewage Sludge	Slow retention time. Maintain 35 °C in AD at all times. Cannot precipitate struvite due to 26% concentration P in effluent.	Recover P, N, NH_4 and CH_4. Created safe compost.	Phosphorous: 37 $mgPO_4\text{-}P{\cdot}L^{-1}$ Ammonia: 395 $mgNH_4\text{-}N{\cdot}L^{-1}$	Methane yield: 370 $mLCH_4{\cdot}gVS_{inf}^{-1}$			[23]
AD + Microalgae	Sewage Sludge and Winery Wastewater	21-30 days for nutrients to be available for plants.	Generates microalgae biomasses for plant fertilisers and bioenergy. Nutrient waste from winery fed microalgae cultivation.	High removal efficiencies were achieved for $N\text{-}NH_4^+$ (97%) and $P\text{-}PO_4^{-3}$ (93%).	CH4 yield increased between 45-70% using co-digestion.			[24]
AD	Dairy Manure	MgO_2 production emissions from struvite precipitation.	Recovered biogas offset 43-60% of the carbon emissions.	8.4 t/day biosolids produced. 919 kg/day struvite produced.	515 kW of electrical power generated.		358 kg/day PHA bioplastics produced per day.	[25]
AD + Electrodialysis	AD Centrate	Had a power consumption of 4.9 ± 1.5 kWh per 1 kg of NH_4-N.	Pretreatment via struvite crystallisation reduced membrane scaling.	NH_4-N concentrated product of 7100 ± 300 mg/L and K 2490 ± 40 mg/L achieved.				[26]
AD-Sequencing Batch reactors + Ultrafiltration	Sewage Sludge		Potential revenue of 2.2–5.9 €/PE year.		Methane recovery up to 4.0 m^3CH_4/PE y.		Bioplastic PHA production of 1.2 kgPHA/PE y.	[27]
FILTRAFLOTM-P reactor (microprecipitation and ligand exchange)	Wastewater	Fouling and hydraulic properties exceeding that of the absorbent limit upscaling. Reactor not commercially accepted.	Proprietary FILTRAFLOTM-P gravity filtration reactor to recover P from wastewater through a filtration/adsorption process in rural areas.	Plant uptake of P achieved was 3.3 ± 0.8 mg P/g dry weight.		Achieved P-concentration of < 1 mg/L of water, acceptable under EU limits.		[28]
Rotating Belt Filters	Toilet Wastewater		Recovery of cellulose materials from toilet paper for improving construction materials flexural strengths.				Recovered cellulosic material up to 26.6 gm^{-3} with maximum solids removal of 74%.	[29]
MEC	Urban Wastewater	18.8 kg carbon dioxide-eq/kg hydrogen emissions from the pilot plant analysis.	Electricity transformation efficiency of 90% and cathodic gas recovery of 90%.		Hydrogen production up to 0.1 $m^3{\cdot}m^{-3}{\cdot}d^{-1}$ was achieved.			[30]
Adsorption	Sewage	Limited adsorption and desorption cycles.	Zeolite ball coated with sulphate used to adsorb phosphate from sewage sludge.	Maximum adsorption capacity of 15.13 mg g^{-1} and equilibrium adsorption of 6.98 mg g^{-1}.				[31]

(*continued on next page*)

Table 1 (*continued*)

Technology	Waste Type	Challenges	Solutions	Nutrient	Energy	Water	Metals/Materials	Source
Flocculation	Mine Wastewater		Sulphide biological oxidation-alkali flocculation process to recover metals and				92.86% sulfide removal and 90.22% sulfur recovery. Average concentration of recovered materials was: 53.93 mg/L, 522.97 mg/L, 34.20 mg/L for manganese, magnesium and aluminium respectively.	[32]
Direct Membrane Distillation	Municipal Wastewater	Regular cleaning against fouling.	No thermal recovery systems.	100% ammonia selectivity. Maximum product concentration (6.4 g NH_4 l^{-1}).				[33]
Bioflocculation – Assimilation Reactor	Aquaculture			50% nitrogen recovery achieved with this system.				[34]
MF-RO	Industrial Wastewater	Membrane fouling precipitation and deposition of inorganic pollutants.	Recover water for industrial cooling and boiler water.			TP had 79.1-100% recovery. Chromium, zinc, iron and lead were also recoverable.		[35]
Packed-Bed Biofilm Reactor	Acidic, Saline Industrial Circuit Board Wastewater	Carbon could still limit denitrification process.	High salinity tolerance of 10% NaCl.	Nitrate recovery from concentrations as high as 5750 mg / L NO_3^-.			Copper, zinc, iron and nickel concentrations with 100% sequestering.	[36]
Fluidised-Bed Reactor	Fluoride Wastewater	Purity is still not at > 95%.	Achieved minimal discharge standards of 10 mg/L in China.				Recovery of cryolite fluoride crystals, > 70% recovery rate, purity > 89%.	[37]
Ion Exchanger	Electroplating Wastewater	Limited to 80 adsorption cycles.	Treats 600 L/h of electroplating wastewater.				Recovery of hexavalent chromium up to 344.7 mg/L.	[38]
MD-Diffusion Dialysis-Reactive Precipitation Unit	Piloting Steel Wastewater	Acid recovery decreases from 93% to 68% with increase in the flow rate.	Plant waste heat is connected to provide heat source for feed solution.				90% hydrochloric acid recovery, iron hydroxide recovery at 99% purity.	
Hydrothermal Pretreatment – Pyrolysis-AD	Sewage Sludge	Required an additional 5.72 t wood pellet/100 t sewage sludge to address thermal deficiencies for pyrolysis.	Heavy metals were immobilised in the biochar.			Biogas combusted to produce steam at 14.34 t/100 t sewage sludge.	Biochar yield was 9.6 t/100 t sewage sludge.	[39]
Hydrothermal Liquefaction	Sewage Sludge	Required higher temperatures to destroy a pharmaceutical.	Micropollutants were all destroyed, > 98% removal rate.				Maximum bio-crude yield of 41% obtained at 325 °C, more than 65 kg biocrude produced.	[40]
Hydrothermal Liquefaction	Sewage Sludge	Difficult to recover nitrogen.	Combined microalgae and sewage sludge processing.	Phosphate recoveries of 97% to 65% by weight from the solution.			Charcoal obtained	[41]

Table 2
Urine resource recovery technologies with an overwhelming focus on nutrient recovery.

Applied Technology		Performance				Ref
Classification	Type	Nutrient Recovery	Water Recovery	Energy Recovery	Material Recovery	
Electrochemical	Reverse Electrodialysis			47-80% Gibbs Energy		[64]
Thermal	Waste Biochar Adsorption	33% N	28.7-31.5			[65]
Membrane	Membrane Distillation		1-15			[66]
Membrane	Membrane Distillation		25.7-30.3			[67]
Membrane	Reverse Osmosis + Concent.	99.9% P; 99.2% K	60%			[68]
Membrane	Reverse Osmosis + Concent.	0.5-13% P; 8.5-52.3 NH_4^+	40%			[69]
Membrane	Reverse Osmosis + Concent.		80%			[70]
Membrane	Forward Osmosis	86.11% NH_4^+-N				[71]
Membrane	Forward Osmosis	98.81% NH_4^+-N				[72]
Membrane	Forward Osmosis		70%			[69]
Membrane	Forward Osmosis	99.3% PO_4^{3-};	90%			[73]
Membrane	Forward Osmosis	75% PO_4^{3-}; 66% NH_4^+;	57%			[71]
Membrane	Membrane Distillation	6.6% KNO_3	80%			[66]
Membrane	Membrane Distillation	~60% NH_3				[74]
Membrane	Forward Osmosis	> 90% NH_3	31.5 and 28.7 L m^{-2} h^{-1}			[65]
Membrane	Gas Permeable Membrane	~90.4% NH_3		0.46 ± 0.01 m^3 m^{-3} d^{-1} H_2		[75]
Membrane	Nanofiltration	18% K			26.32% Na^+; 49.96% Cl^-	[76]
Membrane	Nanofiltration	82% P				[77]
Electrochemical	Microbial Fuel Cell	7-8% N; 7-8% K.		5 kWh/kgN		[42]
Electrochemical	Microbial Fuel Cell	73.1% N; 86.2% P.		21.3 W/m^3; SSP		[43]
Electrochemical	Microbial Fuel Cell			0.192 kWh kg TOC_{rem}^{-1}		[78]
Electrochemical	Microbial Fuel Cell	99% PO_4^{3-}; 42% TN			98% SO_4^{2-};	[79]
Electrochemical	Electrocoagulation	> 90% PO_4^{3-}-P and NH_3-N				[59]
Electrochemical	Microbial Electrolysis Cell			0.152 ± 0.002 m^3 H_2 m^{-2} d^{-1}		[59]
Electrochemical	Microbial Electrolysis Cell	68.7% NH_3-N; 98.6% PO_4^{3-}-P				[60]
Electrochemical	Microbial Electrolysis Cell	95% P		0.28 m^3-H_2/m^3-d; 25 ± 1 to 37 ± 1.7%		[61]
Electrochemical	Microbial Electrolysis Cell			27–46% H_2		[80]
Electrochemical	Membrane-aerated Biofilm Reactor	100% N				[80]
Electrochemical	Electrodialysis	~89% P; ~77% NH_4^+	~81%			[81]
Electrochemical	Electrodialysis – Membrane Bioreactor	65% PO_4^{3-}			54.9% SO_4^{2-}	[82]
Electrochemical	Electrodialysis Concentration	12-48.1% N; 11.5% K				[83]
Electrochemical	Reverse Electrodialysis	52% N; 38% P		47-80% Power		[64]
Electrochemical	Ion Exchange Membranes	77% NH_4^+; 88% K; ~20-30% PO_4^{3-}			> 99% SO_4^{2-}	[84]
Physicochemical	Biochar Adsorption	90% PO_4^{3-}; 37% K				[85]
Biological	Microalgae Photobioreactor	90.5 mg/L.d TN; 4.7 mg/L.d TP				[75]
Biological	Microalgae	90% N; 80% P		254.96 L/kg VS BG; 1.847 g/L BM		[86]
Biological	Microalgae			0.149 ± 0.024; 0.328 ± 0.087 g/m^2/d		[87]
Biological	Microalgae	90% NH_4^+; 58% P		23% Lipid		[88]
Biological	Microalgae	1500 kg/kg VS.d TN; 50 kg/kg VS.d TP; 52% TN, 38% TP		0.34 g VSS/L BM; 285 L CH_4/kg VS		[89]
Chemical	Struvite Precipitation + Ammonia Stripping	99% N; 91% P; 80% K				[90]
Thermal	Vacuum Thermal Stripping	95% P; 95% N				[91]
Volume Reduction	Evaporation	100% P; 74% N				[92]
Volume Reduction	Interfacial Evaporation	100% Na^+, K^+, NH_4^+; TP (R)	1.1 kg·m^{-2}			[93]
Volume Reduction	Evaporation + Chemical Stabilisation	100% P; 92.2% N				[94]
Volume Reduction	Freeze Concentration	3.3-5.8 Conc. N; P; K; 80-92% N-P-K				[95]

(*continued on next page*)

Table 2 (*continued*)

Applied Technology		Performance				Ref
Classification	Type	Nutrient Recovery	Water Recovery	Energy Recovery	Material Recovery	
Volume Reduction	Freeze Concentration	5.1 Conc. TN				[96]

BG = Biogas, BM = Biomass, (R) = Removal, VS = Volatile Solids, TAN = Total Ammonium Nitrogen, TP = Total Phosphorous, TN = Total Nitrogen, VFA = Volatile Fatty Acids, ER = Energy Recovery, API = Active Pharmaceutical Ingredient; AMR = Antimicrobial Resistant, Conc. = Concentrated, SSP = Self Sustained Power, PD = Power Density.

produce power. The rapid depletion of organic compounds, reactor designs, and performance are affected by factors such as electrode types and materials, catalyst types, electrolyte, pH, substrate type, microbes used, DO, reactor designs, oxidation pollution on electrode surfaces and proton exchange membranes [155–161]. Other setbacks of using MFCs for power generation are the low power density (420–460 mW/m^2) [162], volatile voltages, oxidation activation losses, seasonal impacts on microbial growth, biofouling of the proton exchange membranes, treatment of saline wastewater, and high material costs used in its construction [156,159,163,164], and attempts to use cheaper electrode materials were proposed such as pyrite [165,166]. It has been argued that the construction of microbial systems for municipal wastewater plants generates significant carbon footprints [30].

MECs are another form of electrochemical technology for municipal wastewater used to recover nutrients and produce combustible gases. Surface P precipitation [167] and electron-promoting metallic surface coats can improve the economics of MECs [168], given higher current densities led to a 7% increase in P-recovery [169], however, its sustainability and economics are likely to depend on the concentration of nutrients in wastewater, and significant environmental footprints during plant construction [30]. Meanwhile, microbial pretreatment improved simultaneous: biogas production with P-recovery [170] and NH_3-N recovery [171]. Combining AD with MECs led to improved recovery efficiencies in line with other reviews [172–174]. Energy recoveries from oxidative interfacial joule heating [168,175], pico-hydropower devices [176], and H_2 generation [111] could offset power consumption, and when combined with macrophytes could remove heavy metals [177].

Biological resource recovery methods are highly compatible with nutrient-rich municipal wastewater. The challenges for maximising the different types of wastewater recovery are production scalability, recovery productivity, and lack of understanding for combining biological methods with other recovery technologies at larger scales. Identifying high-performing microalgae strains and microorganisms responsible for the conversion of waste and capture of resources are key steps to overcoming recovery-productivity barriers within specific wastewater characteristics.

2.4. Industrial wastewater

Electrochemical technologies are pervasively used throughout the treatment of industrial wastewaters, however, membrane technologies were also equally effective - able to recover dye [206,207], chromium [208], uranium [209], copper [210], and so forth, but suffer from shortcomings in power studies (Table 5). Across industrial membrane wastewater recovery studies, power consumption is rarely studied at the lab scale, whereas electrochemical technologies factor this element as critical to its feasibility on larger scales.

Electrodialysis (ED), for instance, is a heavily used, electrochemical technology for the recovery of precious metals. Copper for one, is the most commonly extracted metal from wastewaters with product purities reaching more than 95% [211]. Although, nickel, chromium, silver, gold, uranium, lithium, neodymium, platinum and chromium (III and VI) were all extractable using electrochemistry.

Micronutrients could potentially be extracted from industrial wastewaters, treated and mixed into creating high-grade N-P-K biofertilisers. The treatment of metals from wastewater has been researched from the lenses of resource removal and preventing environmental damage, however, metallic micronutrients are essential to plant growth and life [212,213]. Besides the recovery of precious metals and removal of toxic ones, no research has been done connecting micronutrient recovery with industrial wastewater [214].

3. Assessment of resource recovery technologies

3.1. Electrochemical technologies

3.1.1. Electrodialysis

ED has been proposed as a gateway for the transformation of wastewater treatment to nutrient and water recovery [298] and is widely used for the recovery of heavy metals. A large proportion of the energy consumed in bipolar membrane ED (BMED) is through ionic dissociations which can be up to 80% [112]. Unwanted diffusions of ammonia can lead to a decline of 40% for its recovery, and a method to counteract this was to raise the pH of the feed solution [75,112]. ED technology integrations with AD and have shown economic cost savings [113] and by changing the area of the membrane recovery rates were improved (Fig. 1a) [299]. Additionally, ED is important in regenerating solutions [300], with Mg and Ca regeneration possible for accelerating P-recoveries [184]. Solution regenerations improved the recovery rates of valuable nutrients and minerals used to facilitate the recovery process.

ED challenges for nutrient recovery include saline wastewater sources which could consume 50% of the total current efficiency from unwanted desalination [113] and the complex heterogenous composition of wastewater [301] requiring treatments to remove harmful chemicals [302,303], APIs [304], or applied to improve struvite precipitation of P [181]. Given solutions produce ammonia in insufficient quantities, liquid-to-liquid membrane contactors can be used to acid strip ammonia before concentrating it with ED to produce an acceptable fertiliser [129]. However, regenerating solutions were shown to increase power consumption in other studies [184,185]. Pressure retarded osmosis (PRO) and reverse electrodialysis (RED) could be used offset power consumption [302,303], however, given that pumps can consume 83% of the recovered power [305], the power recovery for the membrane may not suffice. The major barriers to ED are the significant capital costs from electrodes, pumps and membranes, while operating costs are impacted by scaling, fouling and high energy consumption [168,181]. Resource impurity recovered is another barrier hindering its applications towards CE [168]. Fouling can be addressed through various methods such as electro-ion substituting chemicals with less fouling ones [183] (Fig. 1b), bioflocculation pretreatment [182], electro-reversal and acid cleaning [306]. Nevertheless, it appears that combining ED systems with other water treatment technologies will continue to advance the commercial viability of ED systems [305]. For ED to succeed within the context of CE, renewable energy sources must be utilised with the goal of raising the value of recovered products.

3.1.2. Ion exchange membrane

Ion exchange membranes (IXM) can regenerate and reconcentrate N with the membrane contactors [220]. Nanoparticle doping of IXM

Table 3
Sewage sludge resource recovery technologies showing the versatility of biological, membrane and thermal approaches to recovering resources.

Applied Technology		Performance				Ref.
Classification	Type	Nutrient Recovery	Water Recovery	Energy Recovery	Material Recovery	
Biological	Anaerobic Digestion + Microalgae	99-213 mg N $L^{-1}d^{-1}$; 8-35 mg P $L^{-1}d^{-1}$; ~99% N, ~99% P				[107]
Membrane	Forward Osmosis	99.3% PO_4^{3-}	90%			[73]
Thermal	Combustion			2746 – 5600 MWh		[108]
Thermal	Evaporation/Drying	34-58% NH_4^{+}; 17.1–33.3% TAN		~201 NL kg VS_{in}^{-1}; 64.7% CH_4 yield		[109]
Thermal	Evaporation/Drying		8%			[68]
Thermal	Evaporation/Drying		2.86%			[110]
Electrochemical	MEC	~85% P; 38% TAN		0.08 ± 0 kg-H_2 per kg of TAN		[111]
Electrochemical	Electrodialysis	60% NH_4^+				[112]
Electrochemical	Electrodialysis	35–70% N & P			70% VFA	[113]
Electrochemical	Bipolar Electrodialysis	60% NH_4^+				[112]
Thermal	Hydrothermal Liquefaction	58.6% − 98.5% N; 8.9 ± 0.31 P		59%; 0.49 kg BM	7.1 Mg; 5.9 Al; 9.6 Si; 16.4 Ca; 4. Fe; 3.1 S; 0.1 Cu; 0.2 Co; 2.3 Zn (all g/kg biochar, approx. values)	[114]
Thermal	Hydrothermal Carbonisation	25.3% P; 41.8 mg g^{-1} P		20.5–23.1 MJ kg^{-1} hydrochar; ~95% ER		[115]
Thermal	Hydrothermal Humification				98.8–99.6% Cu; 58.5–98.7% Zn; 86.7–94.4% Pb; 57.4–88.4% Hg	[116]
Thermal	Pyrolysis	29-66% K; 0.2-0.5% P		34.6 MJ kg^{-1}	48% Mo; 2.4% Ni; 1.5% Cu; 0.2% Zn; 0.7% Cr	[117]
Thermal	Pyrolysis			19 MJ/m^3 Gas; 7 kg Biochar		[118]
Thermal + Biological	Microalgae + Hydrothermal Carbonisation		5810 kcal kg^{-1} hydrochar			[119]
Biological	Microalgae Co-Digestion	97% NH_4-N (R); 93% P-PO_4^{3-}		45-70% CH_4; 155.4 and 132.9 NL CH_4 kg VS^{-1}		[24]
Biological + Membrane	Microalgae Anaerobic Membrane Bioreactor Co-Digestion	685 mgN·L^{-1} and 145 mgP·L^{-1} Effluent; 395 mgNH_4-N·L^{-1} and 37 mgPO_4-P·L^{-1} Permeate; 99% N (R); ~25.5-27.4% P		370 mLCH_4·gVS		[23]
Biological	Microalgae Anaerobic Digestion	95% NH_3-N; PO_4^{3-}		49% BM		[120]
Membrane + Biological	Microalgae + Reverse Osmosis Centrate	91.9% TN; 97% TP		27.1-29.3% Lipids	98% Mn; 100% Al; 64% Zn; 62% Co; 50% Ni	[121]
Biological	Microalgae + Bioreactor	68.2-72.3% NH_4^+-N		1056.55 ± 177.65 mg/L Lipids; 483-666 mg/L Glycogen		[122]
Biological	Macrophytes	133 mmol P m^{-3} d^{-1}				[123]
Biological	Macrophytes	53.91% for TP and 99.98% de N-NH_3		680.8-2322.51 NmL-gSV^{-1} BG with 16.04–54.61% CH_4; 1.50 kWh/m^3 Power		[124]
Biological	Anaerobic Sludge Blanket Bioreactor	0.12 g/m^2·day P; 0.79 g/m^2·day N				[125]
Biological	Macrophyte	77-86% NH_4^+-N (R); 91% PO_4^{3-}-P				[126]
Biological	Macrophyte	> 94% of NH_4–N and PO_4–P				[127]
Membrane	Liquid-liquid Membrane Contactors	96% NH_3; 4.6% N				[128]
Membrane	Supported Liquid Membrane	3.8% TN; 3.1% TP; 0.7% K			55 ± 0.5% Cr; 46 ± 4.6% Cu; 50 ± 1.5% Ni; 69 ± 0.9% Zn	[105]
Membrane + Electrochemical	Liquid-liquid Membrane Contactors + Electrodialysis	84-90% NH_3; ~13.2-20.0 L/m^2h NH_3				[129]
Membrane	Emulsion Liquid Membrane	98.7% Ni				[130]

(continued on next page)

Table 3 (*continued*)

Applied Technology		Performance				Ref.
Classification	Type	Nutrient Recovery	Water Recovery	Energy Recovery	Material Recovery	
Membrane	Gas Permeable Membrane	98% NH_3-N; 21 − 133 g N/d per m^2				[131]
Membrane	Gas Permeable Membrane	> 96% NH_4^+				[132]
Membrane	Gas Permeable Membrane	$(NH_4)_2SO_4$ 66.2% − 74.2%				[133]
Membrane	Vacuum Membrane Contactors			67–98% CH_4		[134]
Direct Application	Anaerobic Digestion + Activation + Dissolved Air Flotation	19.5-70.4% N; 14.6-65.9% P; 2.9-7.2% K; all in g kg^{-1} dry weight				[123]

BG = Biogas, BM = Biomass, (R) = Removal, VS = Volatile Solids, TAN = Total Ammonium Nitrogen, TP = Total Phosphorous, TN = Total Nitrogen, VFA = Volatile Fatty Acids, ER = Energy Recovery, API = Active Pharmaceutical Ingredient; AMR = Antimicrobial Resistant, Conc. = Concentrated, SSP = Self Sustained Power, PD = Power Density.

membranes showed improved phosphate recoveries and calcium removal against scaling, and can carbon capture by forming calcium carbonate. The challenges from using IXM technologies is the high membrane costs (denoted by the excessive membrane costs for BMED, cation and anion exchange membranes at \$2100 m^{-2}, \$2472 m^{-2} and \$950 per m^{-2}, respectively) [220]. Despite high membrane costs, the treatment process was still cheaper than using the Haber-Bosch process [220]. The system was quite robust, preserving 90% NH_4^+N recovery rates at 6 kWh·kg^{-1}-N after 6 cycles via spent regenerant base stream that was reused for the next cycle recovered and purified by membrane contactors. The inability to remove dissolved oxygen content (DOC) could also lead to greater fouling propensity, losing out to nanofiltration and ED post-treatment technologies in terms of energy consumption and removal efficiencies respectively, despite the potential to remove 100% of Mg^{2+} and Ca^{2+} [218]. Like ED, IXM technologies can regenerate solutions, recover nutrients, with opportunities to chemically react for carbon capturing.

3.1.3. Microbial electrolysis cells

MECs are an emerging technology used primarily in the space of hydrogen, methane, hydrogen peroxide energy generation and pollutant removals [307]. Microbial activity transfers electrons through the electrodes as a thin biofilm on the anode surface by converting chemical to electrical energy, while setups can also be modified to produce H_2 and methane [308]. The difference between MECs and MFCs is that MFCs produce power [309], while MECs receive electrical power to generate by-products with a cathode isolated from oxygen [310]. MEC power inputs could be used to grow bacteria, promote chemical oxygen demand (COD) removal and electron transfer, and thus, nutrient recovery efficiencies could increase [311]. Recovery efficiencies are impacted by electrode: spacing, surface precipitations, layout, material, crystallisation kinetics and metallic surface deposition [168,169]; and metals such as recover heavy metals such as copper [168], iron [194] and sulphates [192] could also be recovered.

Emerging research works began exploring the use of machine learning to predict H_2 generation, however, the complex nanostructures and inexpensive electrodes substituting platinum as a catalyst [312] and lower energy use [193] make its applications difficult [313]. This will be important given that MEC biohydrogen production from industrial wastewater will be very important [221,223] with a focus on electrode materials [314].

3.1.4. Microbial fuel cell

MFCs oxidise organic compounds into CO_2 while transferring electrons into anodes interacting with microbial cell walls through to cathodes to generate an electrical current [155,157]. The key critical components of MFCs are the cathodes, anodes, membrane separators, and generation of a sufficient biofilm layer [156,165]. There are different variants of MFCs including plant MFCs where performance is dependent on CO_2 concentrations, solar intensity and plant species [155], photosynthetic algae-microalgae MFCs for N-P removal, CO_2 capture and bioelectricity generation (Fig. 2b) [315], constructed wetlands [163] or with soil [165]. There are many designs covering tubular, stacked (series and parallel), up-flow, multi- an single-chamber, sedimentary, photosynthetic and forced-flow MFCs [156,158], whereas stacked MFCs produce the highest power output of the configurations listed [160].

It has been argued that the construction of microbial systems generates a significant carbon footprint [30]. Despite this, MFCs are useful in the sustainable recovery of valuable products and energy [156]. Efficiencies could be increased by enlarging the membrane microstructure surface area for biofilm growth, using composite biopolymer materials, nanofluid doping, modifying membrane properties, adding biochars, improving biomass yields and increasing biofouling resistance [155,164,226]. Adjusting MFC temperature [316], plant species via root biomass (Fig. 2a), microbial methanogenic population alterations

Table 4
Municipal wastewater resource recovery technologies with a largely biological approach.

Applied Technology		Performance				Ref.
Classification	Type	Nutrient Recovery	Water Recovery	Energy Recovery	Material Recovery	
Membrane	Forward Osmosis		31-36 $L\ m^{-2}\ h^{-1}\ bar^{-1}$			[178]
Membrane	Forward Osmosis	7.75-8.09 PO_4^{3-}–P Conc.; 99.3% P	90%			[73]
Membrane	Forward Osmosis	+ 43% PO_4^{3-}-P	11.59 ± 0.49 $L\ m^{-2}\ hr^{-1}$			[179]
Membrane	Air Gap Membrane Distillation	50–91% NH_4-N				[180]
Membrane	Electrodialysis	~75-92% NH_3; 62-81% PO_4^{3-}				[181]
Membrane	Bio-Flocculation -Electrodialysis	100% TP (R); 100% NH_3-N (R); 98.8% K^+; 84.3% NH_3-N			100% TS	[182]
Membrane	Electro-ion Substitution Electrodialysis	> 90% NH_4^+				[183]
Membrane	Electrodialysis	39.9-58.4 mg/L PO_4^{3-}–P; 146.0 – 148.8 mg/L SO_4^{2-}; 64.4 – 67.5 mg/L Mg^{2+}; 119.2 – 134.1 mg/L Ca^{2+}; 291.1 - 307.0 mg/L K^+; 763.2-837.6 mg/L NH_4^+-N; 0.783 kWh/kg NH_4–N; 6.638 kWh/kg Ca				[184]
Membrane	Electrodialysis	4.6-19.2 Conc. NO_3^-; 1.44-4.34 kWh kg NO_3^-	2 - 8 L			[185]
Membrane	Ion Exchange Membrane	> 70% PO_4^{3-}; > 70% Ca				[186]
Membrane	Ion Exchange Membrane	5-10 *Conc. for NO_3- and PO_4^{3-}	80-90%			[187]
Membrane	Membrane Contactors	92.5% N; 481 mg/L.h N; 79-97% P				[188]
Membrane	Membrane Contactors	85% N (R)				[189]
Membrane	Microbial Fuel Cell	49.96-75.02% NH_4^+-N		0.4136, 0.3614, and 0.4964 W/m^3		[162]
Membrane	Microbial Fuel Cell			86.06 $mW\ m^{-3}$ PD; 0.033 $kWh\ m^{-3}$ Net;	99% NO_3- (R); 99% SO_4^{2}- (R)	[190]
Membrane	Microbial Fuel Cell			0.028 kWh/m^3; 74.16 mW/m^3 PD	99.58% Pb; 98.46% Cd; 95.78% Hg; 92.60% Cr; 89.18% As; 82.28% Zn	[177]
Electrochemical	Microbial Electrolysis Cells	75-92% P; 26–2238 kWh/kg P				[169]
Electrochemical	Microbial Electrolysis	80% PO_4^{3-}; 89% Mg^{2+}; 42% Ca^{2+};				[191]
Electrochemical	Electrodeposition	90% Ca (R); 90% PO_4^{3-} (R)				[191]
Electrochemical	Microbial Electrolysis				37.8 ± 12.4- 236 ± 18.1 $mg\ L^{-1}\ d^{-1}\ SO_4^{2-}$ (R)	[192]
Electrochemical	Microbial Electrolysis		0.77 $kWh\ kg^{-1}$ N	0.123 $m^3\ m^{-3}$ Biohythane		[193]
Electrochemical	Microbial Electrolysis				84 mg Fe/L; 154 Fe/L	[194]
Biological	Microalgae	81-99% N; 63-99.95% P; 99- mg N $L^{-1}d^{-1}$ and 8 mg P $L^{-1}d^{-1}$ at 10% blackwater; 9.1 g N g^{-1} and 54.1 g P g^{-1} at 20% blackwater N and P (R)				[107]
Biological	Microalgae	1316.67 kg day^{-1} Animal Feed; 69.23 kg/day N; 7.69 kg/day P		6621.9 kg/day BM; 13.96 MWh/day; 2576.3 kg of Biodiesel; 198.7 kg of Glycerol; 1125.72 kg of Ethanol		[135]
Biological	Microalgae			17.2 g pot^{-1} BM		[152]
Biological	Microalgae			20.7 wt% Biocrude Oil		[195]
Biological	Macrophyte	96-97.6% PO_4^{3-}–P; 43.2-71.5% NH_4^+-N; 94.8-97.4% NO_3^-–N		25.14 mW/m^2 PD;		[196]
Biological	Macrophyte	99% NO_3-; 99% SO_4^{2}-		86.06 mW/m^3 PD		[197]
Biological	Macrophyte			200 ± 36 mL g-VS^{-1}		[198]

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Table 4 (*continued*)

Applied Technology		Performance				Ref.
Classification	Type	Nutrient Recovery	Water Recovery	Energy Recovery	Material Recovery	
Biological	Anaerobic Digestion			183.91 mL/g vS; 84% CH4		[199]
Membrane	Membrane Distillation	50-91% $NH_4^{\cdot}$;	6.7-12.5			[180]
Membrane	Membrane Distillation	460-1920 NO_3^- (mL/L)				[185]
Electrochemical	Capacitive Deionization	83% NH_4^+ (R); 20% NH_4^+				[200]
Electrochemical	Capacitive Deionization	67-89% NH_4^+			90.4% Mg^{2+}; 85% Ca^{2+}; 67.9% K^+; 54.4% NH_4^+	[201]
Electrochemical	Capacitive Deionization	30% NH_4^+ (R); 0.215 kWh/mmol NH_4^+; 20% NH_4^+				[200]
Electrochemical	Capacitive Deionization	81.5% NO_3^-			68.6-74.8% Cl^-; 78.2-38.9-54% SO_4^{2-}; 47.8-48.5% NO_2^-	[202]
Electrochemical	Electrocoagulation + Struvite Precipitation	97.3% TP		2.35 kWh/m^3		[203]
Electrochemical	Electrocoagulation + Struvite Precipitation	24.6% N; 88.4% P				[204]
Electrochemical	Electrosorption	0.085 kWh/mmol NH_4^+; 83% NH_4^+ (R); 46% at 0.55 mmol/L NH_4^+, 29% at 1.38 mmol/L NH_4^+, 21% at 2.77 mmol/L NH_4^+, and 20% at 5.55 mmol/L NH_4^+				[200]
Electrochemical	Electrocoagulation	90% PO_4^{3-}				[205]

BG = Biogas, BM = Biomass, (R) = Removal, VS = Volatile Solids, TAN = Total Ammonium Nitrogen, TP = Total Phosphorous, TN = Total Nitrogen, VFA = Volatile Fatty Acids, ER = Energy Recovery, API = Active Pharmaceutical Ingredient; AMR = Antimicrobial Resistant, Conc. = Concentrated, SSP = Self Sustained Power, PD = Power Density.

and redox potential on methane emissions [317], salinity for power density [163] or antibiotic loads on nutrient recoveries [318]. However, nutrient removal is still the primary goal for many MFC studies [163,166], focusing mostly on power generation despite its possibilities to isolate nutrients through a self-generating electric field (Fig. 2c) [79]. Meanwhile, higher-powered MFC efficiencies depend on cathodes, while lower-powered ones on anodes [319], and for materials aluminium and graphite anodes were suggested for plant MFCs [320]. Given the long-established history of plants capability of removing micropollutants from ecosystems [320,321], plants provide an abundance of organic compounds to bacteria that operate MFCs while offering cleansing properties.

3.1.5. Electrodeposition

The use of electrochemical, electrode-driven systems to reduce or oxidise wastewater solutions down to recover useful products is generally done with valuable metals from wastewater via electrodeposition onto cathode and simultaneous anode oxidation [168] forming a layer of the recovered metal on the surface [322]. Electrodeposition is one of the most critical metal recovery technologies for wastewater [323] and is especially commonly used for the recovery of copper [236], however, other metals can also be recovered. Nutrients such as phosphorous and nitrogen can be recovered through electrochemical ammonia stripping, oxidation and struvite precipitation [13,168,324,325]. The use of bioelectrodes, combined doping between polymers and metals, graphene oxides for high surface area recoveries, oscillating electrodes, nanocarbons [234,326–331] could be used to overcome material limitations in electrodes, costs [332,333] and poor recovery purities [334], and there are still biofouling limitations [332]. Conclusively, ED is a solvent-less, environmentally friendly process for recovering heavy metals [335,336], and is heavily used for industrial wastewater treatment.

3.1.6. Electrosorption

Electrosorption works by selectively absorbing and desorbing ions from a feed solution, commonly through capacitive deionisation (CDI) [322,337–340]. The main limitations for using ES are the limited charging and discharging cycles before performance suffers [341,342]. Electrode materials like activated carbon [200,343,249,253,254,247], soybean straws with pyrolytic carbonisation/biochar [333,344], graphene [248] and carbon cloths [252] can be used to recover or remove ammonia, sulphates, uranium, indium, copper and many more. The use of carbon as a material can be derived from other CE WWTP processes such as hydrothermal carbonisation. A fully integrated CE WWTP space can use hydrothermal technologies to treat sewage sludge and produce ES electrodes as a biproduct [345,346,347] - which are then used and replaced with new waste-derived electrodes. Biomass derived from microalgae feeding on organic solid waste such as fruits, vegetables, and other household organic waste can also be thermally treated similarly to create the electrodes [348]. However, very little research is done in the end-of-life treatment of such spent electrodes.

3.1.7. Electrocoagulation

Unlike chemical coagulation (CC) which requires the addition of chemicals to aggregate impurities for treatment, electrocoagulation (EC) oxidises sacrificial electrodes which releases coagulant metal ions into the solution [349], and has advantages over CC through lower labour costs, zero use of corrosive chemicals, lower total dissolved solids (TDS) in effluent, low secondary pollution, is ~2–3.5 times more cost effective than CC, easier filtration of floc, settleable and relatively inert against acids [350–353]. Both series and parallel arrangements of EC contain sacrificial electrodes, can be powered by solar while recovering hydrogen and providing promising sludge reuses for cement and brick production, and fuel for thermal energy [349]. The use of EC has seen treatments of textile wastewater for dye and toxins removal [354], removal of pharmaceuticals [355], metal removal for potable

Table 5
Industrial Wastewater resource recovery technologies heavily focused on precious metal recoveries.

Applied Technology		Performance				Ref.
Classification	Type	Nutrient Recovery	Water Recovery	Energy Recovery	Material Recovery	
Membrane + Chemical	Forward Osmosis + Chemical Extraction				97.8% Red; 82.1% fuchsin acid; 80.1% orange acid; 76.1% methyl blue	[206]
Membrane	Forward Osmosis		90%		99.5% sunset yellow dye; ~27.6% NaCl	[207]
Membrane	Emulsion Liquid Membrane				~97% Cr (VI)	[208]
Membrane	Membrane Contactors				97% Cu (R)	[210]
Membrane	Hollow Fiber Membrane Contactor				55.7 g Zn·L^{-1} and only 3.2 g Fe·L^{-1}	[215]
Membrane	Hollow Fiber Membrane Contactor				51.3 g·L^{-1} Zn	[215]
Membrane	Hollow Fiber Membrane Contactor				> 90% U(VI)	[209]
Membrane	Emulsion Liquid Membrane				98.7% Ni	[130]
Membrane	Liquid Membrane				64% Al; 17% Ca	[216]
Membrane	Membrane Contactors				Li (93.6% purity)	[217]
Electrochemical	Electrodialysis				92-96% Mg^{2+} and Ca^{2+}; 1.5 Conc. SO_4^{2-}	[218]
Electrochemical	Electrodialysis				84.9-93.7% Zn	[219]
Electrochemical + Membrane	Bipolar Membrane Electrodialysis + Membrane Contactors	9-74% N; 174 g-N·m^{-2}·d^{-1}; 97% N (R)				[220]
Electrochemical	Microbial Electrolysis Cell			0.16-0.06 ± 0.002 $m^3(H_2)$ $m^{-3}d^{-1}$		[221]
Electrochemical	Microbial Electrolysis Cell			78% H_2; 1.16 m^3-H_2/m^3d H_2		[176]
Electrochemical	Microbial Electrolysis Cell			15 mL/L/d H_2		[222]
Electrochemical	Microbial Electrolysis Cell			30.2 ± 1.2 mL (@ 811.33 ± 20 mA/m^2		[223]
Electrochemical	Microbial Electrolysis Cell			2.23 vs. 1.78 mg h^{-1} H_2		[224]
Electrochemical	Microbial Copper Recovery Cell				95.4% Cu (R)	[225]
Electrochemical	Microbial Fuel Cell			1120 mW/m^2		[226]
Electrochemical	Microbial Fuel Cell				55.3-88.2% Cu^{2+} (R)	[227]
Electrochemical	Microbial Fuel Cell			SSP	> 96% Zn^{2+} (R); 83% Zn^{2+}	[228]
Electrochemical	Microbial Fuel Cell				69.9 kg Ag per kWh energy output; 4.25 W/m^2; 99.91 - 98.26% Ag	[229]
Electrochemical	Electrolysis	90% P; 64.7 kWh/kg of P				[230]
Chemical	Precipitation	86% P				[230]
Electrochemical	Electrolysis Electrodeposition	91% PO_4^{3-}—P; 164.96 kWh/kg_{MAP} Struvite				[231]
Chemical	Precipitation	41.52% P				[231]
Electrochemical	Electrochemical Precipitation	94.2% Struvite; 74.2% P				[232]
Electrochemical	Electrodeposition				90% Cu(II); 85-90% Co(II); Ni(II) ~90%.	[233]
Electrochemical	Electrodeposition				Cu 96.5-97.7%; Cd 94.8-97.3%; 98.5% Pb.	[234]
Electrochemical	Electrodeposition				99.4% Cd^{2+}	[235]
Electrochemical	Electrodeposition				Cu 2.45 g kWh^{-1}	[211]
Electrochemical	Electrodeposition				Cu 74.2%	[236]
Electrochemical	Electrodeposition				99.9% Ag, 89.3% Cu^{2+}	[237]
Electrochemical	Electrodeposition				98.5% Pb; 98.7% Zn	[238]
Electrochemical	Electrodeposition				80.22% Zn(II); 71.73% Ni(II)	[239]
Electrochemical	Electrodeposition				94.84% Ni	[240]
Electrochemical	Electrodeposition				100% Ni(II)-citrate; 72% Ni(II)	[241]
Electrochemical	Electrodeposition + Electroreduction				2.22 kWh kg^{-1}Au, 4.45 kWh kg^{-1} Pt, 2.27 kWh kg^{-1} Pd.	[242]
Electrochemical	Electrosorption	95% P			86% Cl^-	[243]

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Table 5 (*continued*)

Applied Technology		Performance				Ref.
Classification	Type	Nutrient Recovery	Water Recovery	Energy Recovery	Material Recovery	
Electrochemical	Electrosorption				0.038 mmol/g NO_3^-; 0.009 mmol/g Cl^-	[244]
Electrochemical	Electrosorption	20% NH_4^+; 0.215 kWh/mmol NH_4^+; 30% NH_4^+ (R)				[200]
Electrochemical	Electrosorption				> 97% Cd^{2+}	[245]
Electrochemical	Electrosorption				99% Cr (VI)	[246]
Physical	Adsorption				87% Cr (VI)	[246]
Electrochemical	Electrosorption				28 mg g^{-1} Cu^{2+}	[247]
Electrochemical	Electrosorption				2510.5 mg g^{-1} La; 2349.25 mg g^{-1} Nd; 2150.75 mg g^{-1} Ce	[248]
Electrochemical	Electrosorption				600 mg g^{-1} La(III); 275 mg g^{-1} Nd(III); 366 mg g^{-1} Ce(III)	[249]
Electrochemical	Electrosorption				1.74 mg·g^{-1}·min^{-1} Li	[250]
Electrochemical	Electrosorption				429.1 mg g^{-1} U(VI)	[251]
Electrochemical	Electrosorption				94.3% UO_2^{2+}; 989.5 mg g^{-1}	[252]
Electrochemical	Electrosorption				7.95 mg g^{-1} In^{3+}	[253]
Electrochemical	Electrosorption				170 mg g^{-1} - 307 mg g^{-1} Phenol	[254]
Electrochemical	Electrocoagulation	74% P; 76% TP				[255]
Electrochemical	Electrocoagulation	1.13–1.50 $kgNH_3$-N/m^2/d; 5.87–7.93 kWh/ $kgNH_3$-N; 56.3-70.9% NH_4^+				[256]
Electrochemical	Electrocoagulation				93.14% SO_4^{2-}; 94.86% Ca^{2+}	[257]
Electrochemical	Electrocoagulation		45–50 L m^{-2} h^{-1}			[258]
Electrochemical	Electrocoagulation				99% Cr(VI)	[259]
Electrochemical	Reverse Electrodialysis			0.482 W/m^2		[259]
Electrochemical	Electrocoagulation			70% H_2	> 97% Blue Dye (R)	[260]
Electrochemical	Electrocoagulation				Cu 82.49% (R); CN 95% (R); 71% Grease	[261]
Electrochemical	Pulsed Electrocoagulation				97.5% Sb (R)	[262]
Electrochemical	Electrodeposition + Electrocoagulation				> 97.4% Ag^+	[263]
Electrochemical	Electrocoagulation				100% Oil	[264]
Biological	Microalgae	94.6% TP; 80.7% TN		0.37 g/L/d BM; 12.5% lipids; 18% Protein		[265]
Biological	Microalgae	60.75% TN; 71.81% NH_4^+-N; 96.13% TP		44.57% Protein		[144]
Biological	Microalgae			14.49 MJ.$m_{vinasse}^{-3}$		[266]
Biological	Microalgae	94% N; 100% PO_4^{3-}-P		179 mg g^{-1} DW BM		[267]
Biological	Microalgae			20.7 wt% Oil		[195]
Biological	Microalgae	49.7% TN; 21.8% TP; 42.5% K		4.61 g/L BM; 3.6 g/L Lipids	37.2% S	[268]
Biological	Microalgae	4.45 mg/L h^{-1} TN; NH_4^+-N < 17.7%; 100% NH_4^+-N (R); 87.8% TIN (R)		43.85% Dry Weight BM		[269]
Biological	Microalgae			54.12% Glucose; 1.4 g/L BM; 116.2 mg g^{-1} Ethanol (3 G)		[143]

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Table 5 (*continued*)

Applied Technology		Performance				Ref.
Classification	Type	Nutrient Recovery	Water Recovery	Energy Recovery	Material Recovery	
Biological	Microalgae				99% Cr(III) (R); 100 mgL^{-1} Cr(III) (R)	[270]
Biological	Microalgae	65.17% PO_4^{3-}; 77.49% NH_4^+		24.78% BM		[271]
Biological	Macrophytes				83 ± 4.4% Fe; 66 ± 1.4% Cr; 63 ± 42.4% Cu; 76 ± 3.4% Cd; 79% for Zn; 67 ± 2.4% Ni; all (R)	[272]
Biological	Macrophytes + Microbial Fuel Cell			0.015 kWh/m^3	99.58% Pb, 98.46% Cd, 95.78% Hg, 92.60% Cr, 89.18% As, and 82.28% Zn; all (R)	[177]
Biological	Macrophytes				18% Cd; 47% Pb; 64% As; 56% Cr	[273]
Biological	Macrophytes				17.23 mg As/Kg, 116.6 mg Pb/Kg, 330.5 mg Ni/Kg, and 342.9 mg Cr/Kg	[274]
Membrane	Gas Permeable Membrane	100% P; 70% NH_4^+ (R)				[275]
Chemical	Precipitation	95-97% P (R); 92.8-94.9% NH_4-N; 97.4-99.1% P				[275]
Membrane	Gas Permeable Membrane	> 96% NH_4^+				[132]
Membrane	Gas Permeable Membrane				54.7% Cationic dye; 69.2% Alizarin yellow R; 89.6% NaCl	[276]
Membrane	Gas Permeable Membrane				57% Acetic Acid	[277]
Membrane	Support Liquid Membrane				94.3% Cd(II)	[278]
Membrane	Support Liquid Membrane				100% Cr(VI)	[279]
Membrane	Support Liquid Membrane				99.4% Cu(II)	[280]
Membrane	Support Liquid Membrane				93 ± 4% Zi	[281]
Membrane	Support Liquid Membrane				64.89-82.31% Bi(III)	[282]
Membrane	Support Liquid Membrane				99.5% (wt.) Ag	[283]
Membrane	Support Liquid Membrane				22.9% Nd^{+3}; 3.2% La^{+3}	[284]
Membrane	Support Liquid Membrane				> 95% Pd	[285]
Membrane	Support Liquid Membrane				Pt(IV) 100%; Rh(III) 100%	[286]
Membrane	Support Liquid Membrane				> 90% U(VI)	[287]
Membrane	Support Liquid Membrane				50.2-52.6% Hg	[288]
Volume Reduction	Interfacial Evaporation		1.43 kg m^{-2} h^{-1}			[289]
Volume Reduction	Interfacial Evaporation		1.16-1.35 kg m^{-2} f			[290]
Volume Reduction	Freeze Concentration				97.9% Ni^{2+} (R)	[291]
Volume Reduction	Freeze Concentration + Microalgae				601.2 mg g^{-1} U	[292]
Biological	Microbial				40-67% PHB Bioplastic	[293]
Biological	Microbial				78.78 ± 0.57% PHB Bioplastic	[294]
Biological	Microbial				74 ± 8% PHA Bioplastic	[295]
Chemical	Chemical Valorisation				77 - 98 ± 2% PHB Bioplastic	[296]
Chemical	Chemical Valorisation				7-51% PHA Bioplastic	[297]

BG = Biogas, BM = Biomass, (R) = Removal, VS = Volatile Solids, TAN = Total Ammonium Nitrogen, TP = Total Phosphorous, TN = Total Nitrogen, VFA = Volatile Fatty Acids, ER = Energy Recovery, API = Active Pharmaceutical Ingredient; AMR = Antimicrobial Resistant, Conc. = Concentrated, SSP = Self Sustained Power, PD = Power Density.

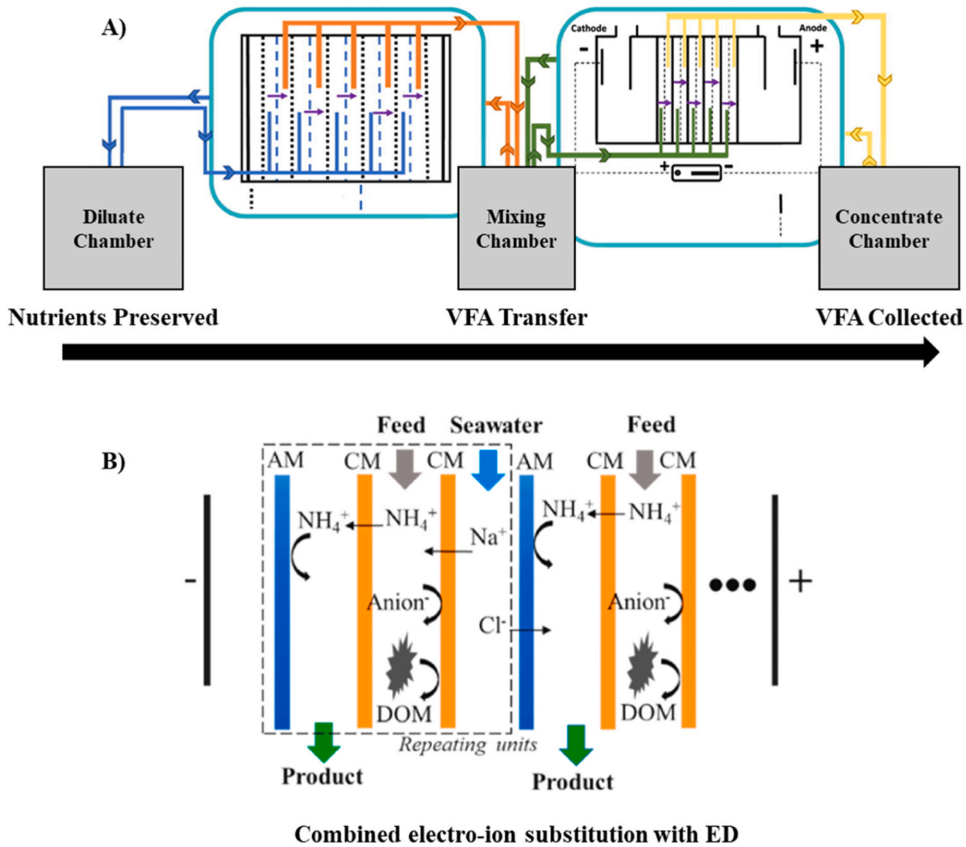

Fig. 1. A) Nutrient concentration on one side while speeding up the VFA extraction process with combined ED and MD, b) NH4+ recovery at lower power consumption when electro-ion substitution is combined with ED.
A) modified from Brown et al. [299], b) modified from Meng et al. [183].

water and industrial wastewater, oil removal for water [356] and oil [357] recovery – mostly industrial wastewater treatment. Current densities, pH of solution (dependent on electrode material and type of pollutant), configuration, contaminant and pollutant concentrations, distance of electrodes, electrode materials (commonly aluminium, iron and magnesium) and arrangement, electrolyte used, electrolysis time, and reactor design are all important contributors to the performance of EC [203,204]. Power consumption has been a contentious issue within EC, compared to membrane distillation (MD) seen in Sardari et al. [258] that could use low grade waste heat and hydrogen co-generation with the potential to offset energy costs [260]. Biochars (Fig. 3a) [205], CC [255] or conversion to P-recovering MFCs (Fig. 3b) [358] can be used to lower EC power consumption. EC can help seed microalgae for P-harvesting [141] and deployed alongside for pretreatment, water recoveries and impurities flocculation [258]. EC coupled with other systems yielded promising CE benefits including simultaneous electricity-P recovery [359], ammonia-contaminant removal [256], forward osmosis (FO) and MD integrations for water recoveries [258], EC-electrodeposition for Ag recovery [263], EC-ES [205], EC-RED for Cr removal and power generation [259], flocculation for microfiltration [360] - all yielded promising results for treating wastewater and recovering products. However, fouling [256] and chemisorption [257] are still barriers – which require better design and operating conditions, increased sludge reuse and hydrogen production [349] to improve the economics of CE EC. Some examples of these include not limiting the current density beyond 60 A/m^2 to maintain ammonia recovery rates higher than 60% [256], when used as pretreatment with FO to obtain water recoveries of 30% [258], sourcing from solar power with H_2 generation [260] and pulsing electrodes at 400 Hz to achieve Sb removals of up to 97.5% [262]. Therefore, EC demonstrates promising levels of pollutant removal and power production characteristics.

3.2. Membrane technology

Fig. 4 shows the membrane technologies available for resource recovery throughout wastewater. Reverse osmosis (RO) (Fig. 4a), FO (Fig. 4b), MD (Fig. 4c), support liquid membranes (Fig. 4d) and gas-permeable membranes (GPM) (Fig. 4e) are used throughout the recovery of resources. They are primarily used to concentrate dilute feed solutions into concentrates for better resource extraction.

3.2.1. Reverse osmosis

RO is an established and effective technology in reducing both harmful and useful products within waste streams [361]. Besides ED, RO is one of the other technologies that can concentrate brine with nutritional content [362]. It is possible to achieve zero-liquid discharge using RO, where the brine could then be further treated using FO, PRO, ED, volume reduction technologies, advanced oxidation, adsorption, coagulation, ion exchange, and struvite recovery and ammonia stripping [362]. The emerging nature of ED, FO and PRO technologies commonly experimented with RO [361] may limit its applications for multi-process CE recoveries – which has become essential for maximised resource recoveries [363]. Meanwhile, wetlands are proving to be one of the most socially and economically viable combinations to RO [364,365]. In fact, pressure-driven membrane processes remain as the preferred choice for saline wastewater resource recovery, and combined integrations with other processes are required to maximise recovery opportunities [363]. Heavy metal and nutrient rejections as high as 98–99% could be achieved [366], in particular, the nutrients can be used to harvest microalgae [367] supported by the lower-than-average costs to concentrate it [367,368]. Moreover, susceptibility towards concentrating heavy metal pollutants in nutrient solutions [369] negatively affect its reusability in agriculture as a fertiliser.

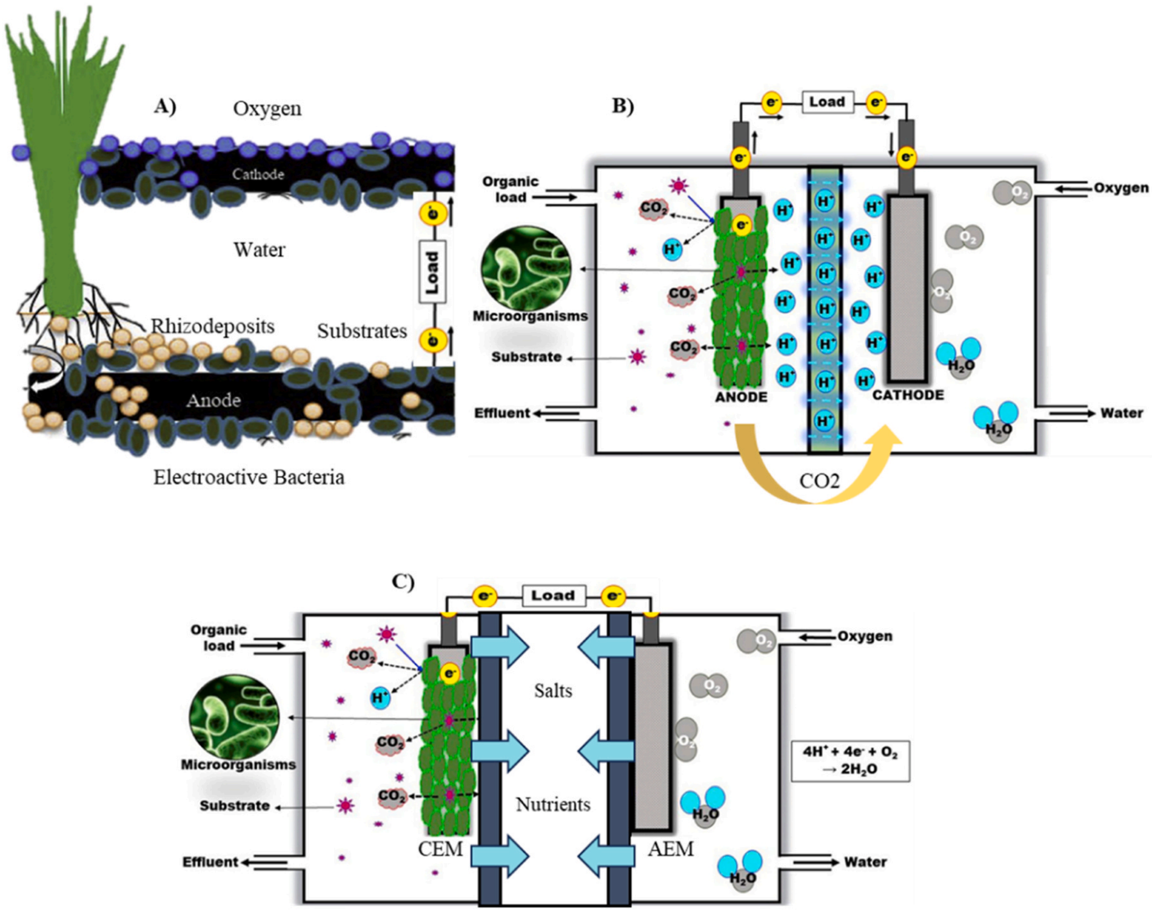

Fig. 2. a) Constructed wetlands with natural cathode and anode setup for plant MFC for heavy metal recovery and bioelectricity generation in rhizosphere rich environments. b) Conventional MFC showing the conversion of CO_2 into H_2O to produce electricity, c) Modified MFC to capture nutrients and other resources between the anion and cation exchange membranes while generating electricity
(a) Modified from Kabutey et al. [320], b) modified from Palanisamy et al. [164], c) modified from Palanisamy et al. [164] to match Lu et al. [79].

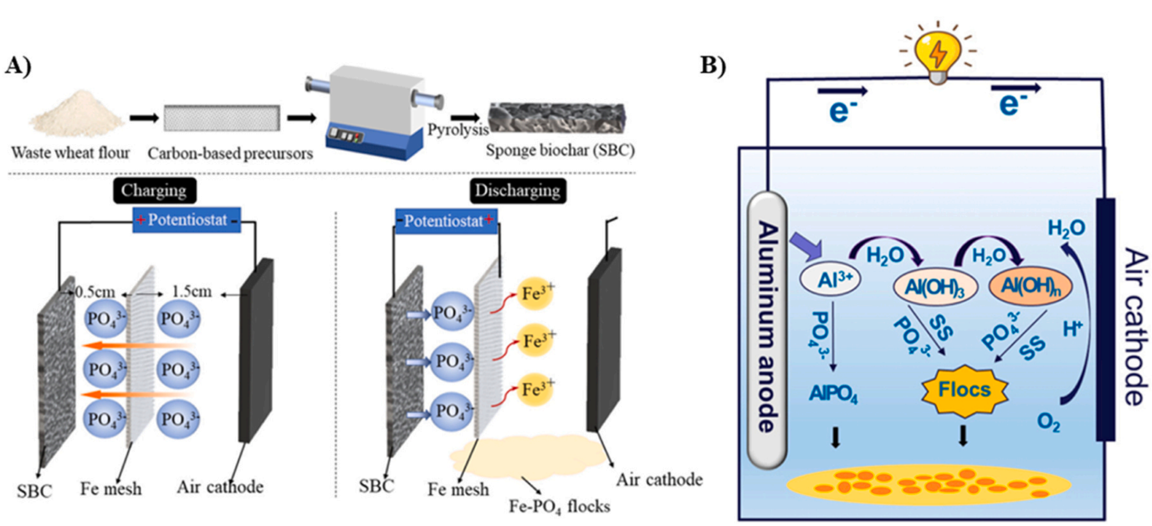

Fig. 3. A) Biochar electrodes made from waste wheat flour which can absorb phosphate nutrients and electro-desorption into the sacrificial iron creating phosphate-iron flocs collection, b) Combining H+ with O_2 through a fuel cell design to generate electricity and recover phosphate.
A) Adapted from Tian et al. [205], b) Adapted from Han et al. [358].

3.2.2. Forward osmosis

An emerging membrane technology, FO uses the osmotic forces between two solutions of different concentrations. The feed solute (FS) water content permeates to the draw solute (DS) side of the membrane [370]. FO is rarely used as a standalone technology and is used in many different configurations such as with RO for discharge treatment [371] and for DS concentration [70] with MD [67]. Industrial wastewater such as dye and water can be recovered through FO [207] and shale wastewater for calcium, barium, and salt through FS [178]. Membrane surface amine functionalization [372], interlayering design [373], selective layer coating [207], membrane grafting [372] are methods to improve resource selectivity. Biogas sparging could be used to reduce fouling and enrich FS nutrients by 200% and 800% respectively, raise biogas productivity by 45%, and its agitative effects lowered fouling by 95% [374]. (Fig. 5). In this study [374] however, FS enrichment levels were hampered due to the low rejection rates for NH_4^+ ions, and could potentially be remedied by raising the pressure on the DS side, or the acidity as seen in Volpin et al. [65], however, ammonia leakage is an issue with FO-MD [67]. Fertiliser drawn FO could be used in applications such as palm oil water recovery [375], polluted water for irrigation [376], and urine N-P-water recovery [63].

Like all other membrane technologies, fouling and scaling remain as barriers [70,377], however, anti-fouling effects were noted through grafting [72,72], through pH and temperature FS [378] and DS alterations [379], and lowering reverse salt flux (RSF) [378]. Meanwhile, no sufficient strategy to manage FO DS still remains [71]. Fouling, frequent membrane cleaning, low water flux, RSF, concentration polarisation, and economic viability are barriers to FO resource recovery adoption, while many of the FO studies were focused on nutrient concentration and water recoveries [371,380,381], or combining it with pressure-retarded osmosis for osmotic power generation [370]. Given the emerging nature of PRO and FO membrane technologies, the market for these is still small [370,382]. Current and future studies are exploring further coupling of FO with other resource recovery technologies and CE applications such as with MD for potable water recoveries from urine with applications in space [383], recycling RO membranes for FO [384], raising water recoverability and brine recyclability [385], and nutrient and water recoveries of between 84–98% and 74% respectively when combined with ED [386].

3.2.3. Membrane distillation

For WWTP CE, MD studies primarily use concentrated urine for nutrient recovery, but can be integrated with other wastewater resource recovery setups. Selective ammonia recoveries of about ~60% could be achieved [74]. McCartney et al. [74] study aims to find energy-efficient alternatives to the Haber-Bosch process for N-recovery through isothermal MD setups, in other studies, ammonia leakage to the permeate side is undesirable through high temperature volatilisation [66]. The type of MD appears to show different performances to rejecting ammonia seen in Davey et al. [180], versus direct contact MD setups with lower ammonia rejections [66].

Membrane fouling, ammonia leakage, non-renewable energy consumption, salinity buildup and wetting are issues facing MD [387]. To prevent ammonia leakage, experimented strategies such as better membrane thickness and porosity, and acidifying the feed [65] could be done. MD as pretreatment has been suggested to recover and prevent the loss of nutrients [383]. Therefore, membrane designs affect nutrient recovery reconcentration efficiencies.

It has been proposed that AD recovered biogas can be used to heat the feed for MD to mitigate energy costs [387]. Combining MD with solar for ammonia recovery dropped the costs from US$9.20/kg to US$5.11/kg - yielding a net profit of $0.83/m^3 [388]. MD coupling with FO, membrane bioreactor (MBR), crystallisers and PRO/RED has the potential to recover biogas, nutrients, electricity which can help eliminate foulants, and mitigate technical

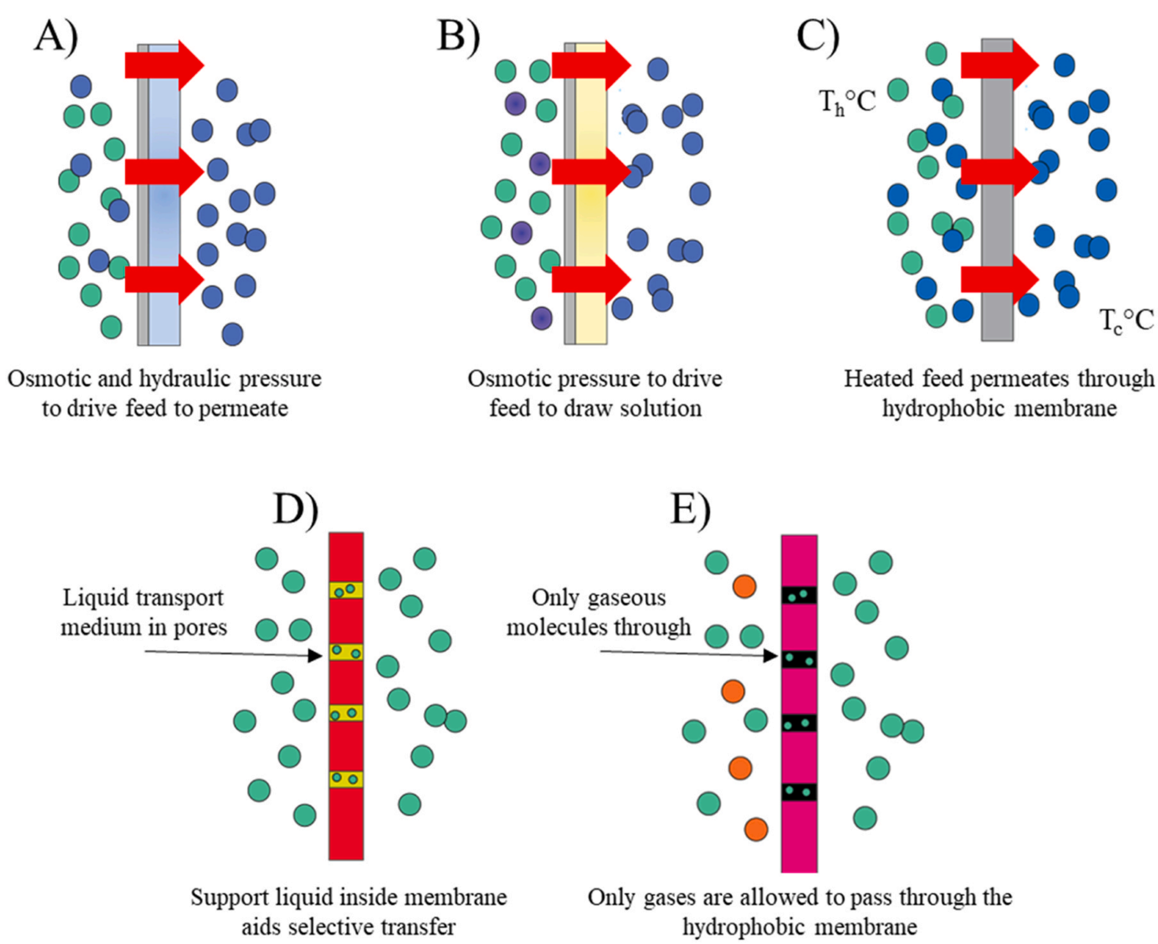

Fig. 4. a) RO, b) FO using osmotic pressure between solutions of different concentrations to draw resources from feed to draw side, c) MD requiring heated feed to permeate through a hydrophobic membrane, d) support liquid membrane with the use of a solution within the membrane pores to transport selectively the resource, and e) GPM which only allows gaseous molecules through to the other side.

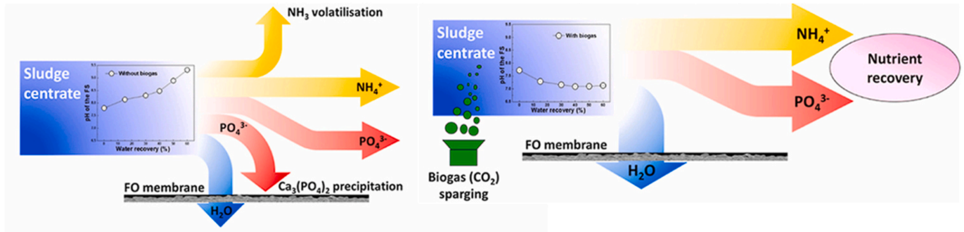

Fig. 5. Biogas sparging to reduce precipitation on membrane and increase direct nutrient recovery.
Adapted from [374].

standalone disadvantages [389]. The use of MD-Crystalliser systems to eliminate liquid discharge and recover valuable solid products is possible [389,390], therefore, enabling zero waste generation and closing the WWTP CE cycle. MD is increasingly being used for ammonia recoveries and zero-liquid CE WWTP setups; however, its main challenges arise from high thermal energy consumption.

3.2.4. *Supported liquid and membrane contactors*

Support liquid membranes separate two solutions in similar phases which enable the recovery of valuable products. These include the selective recovery of NH_3 [128,129], NH_4 [132]. For industrial wastewater, nickel can be recovered [129]. Support liquid membranes could recover much heavier metals and in particular, a much broader range [105] of products. Emulsion liquid membranes form micro bubbles through agitation which selectively absorb valuable products within a feed, and are especially useful for metals [391]. The stripping phase is situated inside the bubble beyond the membrane phase layer. Recovery product and surfactant concentrations were known to impact recovery rates the most [392]. Meanwhile, stirring speeds and retention/extraction times could affect recovery efficiencies [393]. One of the cited challenges for emulsion liquid membrane approaches is the lack of a continuous recovery process, long residence times and poor recycling of emulsion solutions [392]. With this, liquid membrane technologies have now begun considering green solvents for the removal and recovery of heavy metal pollutants.

Membrane contactors on the other hand do not use liquid-liquid contact mechanisms, and instead, are separated by a hydrophobic membrane with a stripping solution or gas against the feed. Heavily polluted wastewaters can have nutrients and valuable metals recovered without severe performance hindrances [188,209,215,217]. Membrane transfer resistances and designs remain a challenge for optimising the recovery of products [217].

3.2.5. *Gas-permeable membrane*

In GPM resource recovery is primarily nitrogen [132,133], and this is done through a hydrophobic membrane that recovers only gas [394]. Membrane designs can exist in flat sheet [133,395] and tubular [275,396]. Removal and recovery efficiencies are 66% [133] to 98% [131], and these processes consume alkalinity requiring higher pH of around 10–11. GPM can be coupled with electrochemical technologies to improve the recovery efficiencies of the system by concentrating gaseous products into the GPM exposed side [397,398], and experimented with algae to add a further \$0.09 m^3 of revenue per water unit treated [399] through the sewage treatment and resource recovery systems. The N product purities can achieve acceptable Environmental Protection Agency standards [396], therefore, GPM can serve to add bottom-line revenues to CE WWTPs. Given its antifouling properties [395], this membrane requires less cleaning and maintenance. The potential for CH_4 recoveries through GPM using AD remain [10,400] however, the efficiencies in doing so are still unclear.

3.3. *Thermal technologies*

3.3.1. *Hydrothermal methods*

Hydrothermal carbonisation (HTC), treatment (HTT) or liquefaction (HTL) processes elevates an organic digestate with higher water content to between 180–250 °C in a sealed environment to maintain the liquid nature of water, turning it into a solvent, catalyst and reactant for hydrolysis and decarboxylation [401], although, temperatures as high as 250–400 °C at a pressure between 50–250 bar were experimented [402] (Fig. 6), and the performance of hydrothermal technologies is dependent on the reaction temperature or catalyst [403] and time [404]. The end product is biochar which can be used as an energy source, plant fertiliser [401] or made into electrodes [205]. Biocrudes [114,403] and hydrochars [405] could be recovered for its energy. Fertilisers from HTC via inorganic P are preferred [406] and obtained through Mg added to AD influent [407], and could also be obtained through microalgae biomass with best strain selections [408] grown in concentrated HTL-aqueous solutions [114,409]. The solid phase of HTL (hydrochar/biochar) contains many valuable metals such as copper, iron, zinc and manganese [403,410], however, toxic metals could leach out [115] but could be absorbed to render the fertiliser safe using humic substances [116]. Consequently, pyrolysis and HTL are two technologies that can produce biofuels/biocrudes from microalgae, however, they are not technologically mature and economical enough for commercial-scale application [411]. Fig. 6 shows all of the potential products that can be recovered from the processing of biomass and sludge for production, with Fig. 7 showing all of the useful products aforementioned that can be recirculated.

Presently, there are issues with the use of HTL being reactor corrosions, plugging and choking; scalability of high-pressure equipment, poor simulation characteristics, accumulation of inhibiting chemicals, energy-intensive drying, high capital costs and expensive catalysts that deactivate with time [412]. There also appears to be a compromise between hydrochar production and valorisation, hydrochar dewaterability, AD biogas production, and energy consumption regarding temperature adjustments and holding periods [413]. Machine learning is newly being applied to predict hydrochar content and heating values [414,415], however, the limited datasets lower accurate predictions [416].

3.3.2. *Pyrolysis*

Pyrolysis heats dried organic matters in an inert atmosphere which breaks down into three phases: biochar, bio-oil and a non-condensable gas [117], and differs to HTL where its process relies on water as a reaction medium [402], however, sludge water contents of up to 78% were experimented [117]. CH_4 and H_2 component of the non-condensable gas can be burnt to power the pyrolysis reaction, the biochar can be used as a soil conditioner or carbon-neutral fuel, and the bio-oil as fuel or processed for further refinement into other chemicals [418]. Pyrolysis presents many opportunities for CE in terms of energy and nutrient recycling - expanding opportunities for WWTPs to become carbon neutral.

There appears to be a trade-off between raising the pyrolysis temperature, and the biochar, oil and gas yields [117]. The study [117]

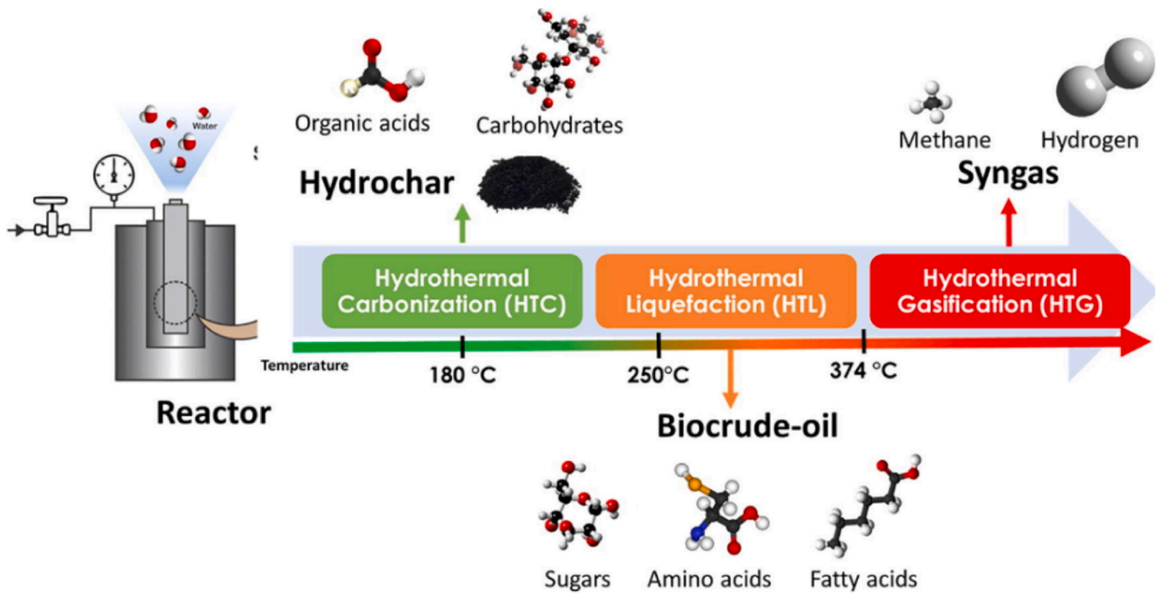

Fig. 6. Showing the various hydrothermal heating phases yielding various products from biowaste.
Modified from Lachos-Perez et al. [417].

found that slow pyrolysis at 10 °C min^{-1} between 300–500 °C, had lower heavy metal leaching and higher hydrochar yield. For a pyrolysis plant processing 2.1 tons dry solids per hour, a capital investment cost of 13.5 million CAD and operating expenses of 1.32 million CAD y^{-1} was required [117]. Moisture in sludge is a huge problem towards highly efficient pyrolysis due to high enthalpy for evaporation. These findings aligned with that in Salman et al. [108] where more than 50% of the sludge's energy was consumed to remove moisture content. Unfortunately, it appears that - with an lifecycle assessment analysis - pyrolysis was one of the least environmentally friendly methods to recover energy unless resource CE recovery was high [419]. Meanwhile, co-pyrolysis could overcome barriers regarding heavy metals by converting them into a residual oxidised state and improve biooil production.

3.3.3. Gasification

An extension of pyrolysis – gasification - is another thermochemical method aimed at creating solid ash and a combustible gas under a partially oxygenic atmosphere under an exothermic reaction at higher temperatures of around 1100 °C. This step typically occurs after pyrolysis generates process waters, non-condensable gases and solids – where such products are then converted into a combustible gas. Gasification has been proposed as an environmentally friendly technology to lower emissions, landfill disposal, and solid waste management; and the range of technologies include fixed bed, fluidized bed, entrained bed, rotary kiln, plasma gasification and chemical conversions of feedstock [420]. As the name implies, gaseous products are recovered, and there are general concerns surrounding air pollution from combustion. Nevertheless, solid macronutrients and gaseous recoveries were possible with this technology [421].

3.3.4. Biochar and biomass ash reuse

Biochar, biomass and ash are extremely versatile materials for use in a wide range of settings in CE WWTPs. Such materials could be used to eliminate pharmaceuticals within urine for nutrient recovery [422], as solar absorbers for interfacial steam evaporation in photothermal water purification [423] and desalination [424], pre- and post-treatment of water [425], metal removal [426,427], and materials for membrane components [425]. They can also be modified through acid, alkali and oxidative treatments to change the surface morphology and microstructure to enhance adsorptive properties [428] and facilitate struvite precipitation [429], metallically treated to selectively attract certain metal pollutants [427]; combined with nano-composites [425]; eluted in solvents to reuse or extend the life of biochar [430] or used for soil remediation [431]; soil stabilising against harsh weather [432]; and for increasing crop yield productivity [433].

The benefits of using biochar could lead to lower water use, nutrient recovery (N and P), energy recycling, micropollutant and pathogen removal, and recovery of heavy metals [434], and are displayed in Fig. 8. The substitution of fossil fuel with sustainably-derived biochar had a more profound effect on global warming impacts compared to material substitution [435,436]. There are issues surrounding the degradation of brick strength through CO_2 reactions [437], and unknown efficiencies for biochar interactions with microorganisms, contaminants and plants [438]. Biochar is used as a soil remediator [439] at the right given quantities [440] – with excessive applications leading to soil P and N leaching [441]. The cost savings for consumers and waste management could be significant with the price of sewage sludge biochar was $US246/ton compared to $US1500/ton for activated carbon [442] and save waste management costs of $US 195,000 per year [443]. Tian et al. [444] found significant variations in the price of biochar ranging between $50 to $1900/t which can drastically affect the accuracy of sizing biochar markets, therefore, forecasting commercial opportunities for this product will be difficult. Nevertheless, biochar is expected to play a critical role in the sustainable CE for WWTPs in the future.

3.4. Biological recovery methods

3.4.1. Microalgae

Microalgae as a tool for recovery has the benefits of CO_2 capture, waste valorisation, volatile organic compound elimination, fertiliser biomass, biofuel conversions, water treatment, nutrient recovery, electricity generation, glycerol recovery - non-exhaustively across pharmaceutical, industrial, dye and municipal wastewaters [135,136,147]. In severely polluted wastewater bodies, cyanobacteria can thrive and bioremediate wastewater polluted with heavy metals [445,446] and its mixture can boost hydrogen production by 50–60% [447] by supplying oxygen [148]. Microalgae consumes large quantities of nutrients to primarily produce biofuels [88], hydrochar coal [119], soil restoration products [448], direct fertiliser [150,152] and emerging nutraceuticals [449,450]. Inhibitors for microalgae include

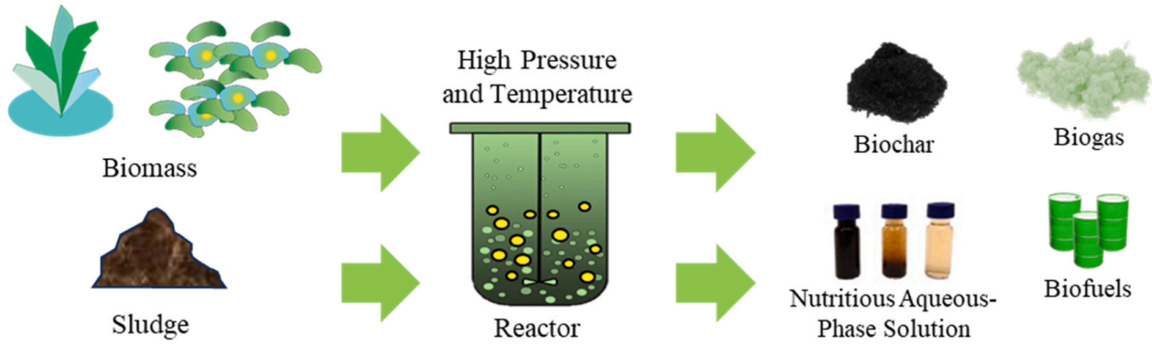

Fig. 7. Hydrothermal treatments with input wastes such as biomasses, sewage sludge, feedstock and other organic wastes are pressure heated to produce biogas, nutrient-rich solutions, biochar and biofuels.

wastewater salinity [451], carbon and ammonia concentrations [445,452]. Other challenges to microalgae CE are difficult simulations of heterogenous wastewater conditions, inoculum seeding, biomass or hydraulic retention time (HRT), the selection of microalgae suited for the conditions, correct nutrient C/N and N/P ratios, and prevention of nutrient loss [145,146]. Currently, upscaling microalgae technologies is the biggest barrier with pilot plants barely making up > 100 m^2 in footprint [453], with genetic modifications for microalgae proposed as a solution to overcome this issue [454]. Despite this, microalgae demonstrate extreme versatile recovery applications across municipal and industrial wastewaters.

3.4.2. Macrophytes

Macrophytes perform similar functions to microalgae but are visible to the naked eye and are commonly on constructed wetlands for remediation [455,456]. Biofuels, biohydrogen, biogas, biodiesel, biomass for fertilisation and animal feed, biochar, biosorption and absorbents are all valuable products that can be made from using macrophytes for CE [457,458], but require substrates to thrive such as hydrochar, oyster shells - where the primary P-recovery mechanism is via substrates [459,460]. The macrophytes involved commonly include duckweed, water lettuce and water hyacinths [461], however, there are many species of macrophytes that could be experimented with. The plants can be used to simultaneously pre-treat wastewater and enhance power generation via fuel cells through improved microbial diversity, ammonia removal, and biomass decomposition [462]; and by producing both biomass and oxygen in the water while removing nutrients and chemical oxygen demand to produce food for bacteria that power fuel cells which take place in the rhizosphere of plant roots [162,177,190,196]. These plant species are versatile for treating industrial wastewater in heavy metal recoveries, [274], treatment of tannery [463], dye wastewater [273] for COD removal, and pretreatment for improved MFC power generation [464,465] – however, treatment performances for macrophytes can be affected by pesticides [466,467], membrane biocides [468], heavy metal saturation limits [272,274], and climate [464]. Polyculture macrophyte communities, combining with worms for anaerobic sludge volume reduction, addition of magnesium, HRTs, pH levels, appropriate dilutions, genetic modifications, addition of nickel oxide nanoparticles, steam-exploding for AD [123,126,127,198], are all methods to improve nutrient and energy recoveries while increasing biomass yields when treating contaminated wastewater, however, greenhouse gas (GHG) footprint [469] and substrate reuse [464] are all issues that need further studying.

3.4.3. Anaerobic digestion

AD can use adverse range of feedstocks as substrates including food wastes, farm and garden waste, biomass, industrial waste and animal manure - can be used as AD substrates. Co-digestion is regarded as the superior form of AD [101], although, performance will depend on the feedstock type. Review papers previously discussed biochar [470], organic food waste [406], livestock substrates [471], hydrothermal pretreatment [199,406], nitrification/denitrification and P-precipitation [472], and microalgae [473] for CE with AD to enhance methane, shorten HRT, remove micropollutants, reduce landfilling and GHG emissions, cultivate microalgae, improve biorefinery, promote energy recoveries and produce biofertilisers [470] (Fig. 9). AD is regarded as the most environmentally friendly approach to managing organic food waste [474], with incineration being the cheapest, yet, less eco-friendly option.

Composting [475] is the approach that AD uses to recover nutrients for agriculture use as it can eliminate pathogens. Composting is rated as the worst resource recovery option according to Tarpani et al. [419]. Direct applications can also be employed from AD, however, nutrient concentrations are below commercial acceptability [476], heavy metal presence can exceed regulations [477] which pose a challenge in countries with weak measurement mechanisms for AD [475].

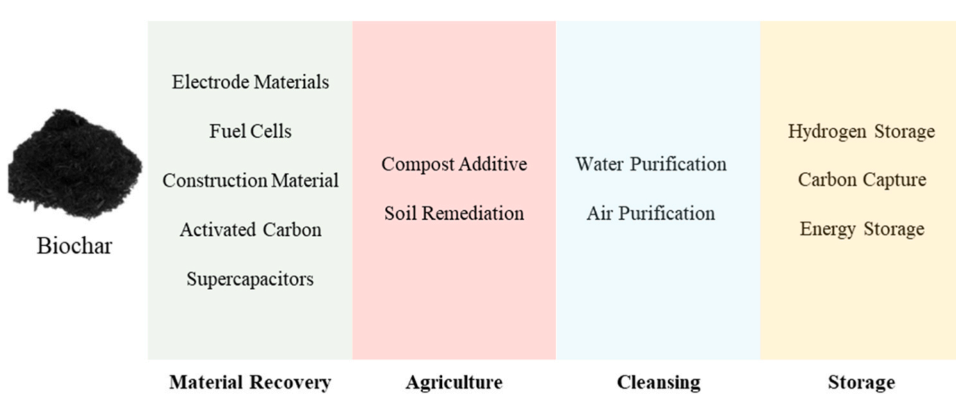

Fig. 8. Biochar as a material produced from hydrothermal processes has a wide variety of applications particularly within industrial, construction, agricultural, environmental and renewable power and carbon storage sectors.

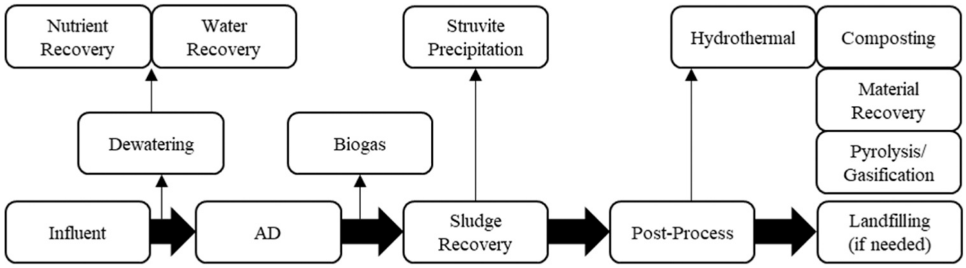

Fig. 9. Resource recovery throughout the AD process showing the multiple biproducts that can be extracted from sewage sludge.

Landfilling is also set to be banned across the EU based on Directive 86/278/EEC [478]. The cost of sludge direct application on agricultural lands is €120 to €375 per ton of dry solids and is regarded as the most effective sludge management strategy [479]. With AD, various products can be recovered by tapping into the process at different points (Fig. 9) which expands many opportunities to recover and integrate different WWTP technologies for sewage sludge CE.

3.5. Concentration/volume reduction methods

3.5.1. Freeze concentration

There are direct and indirect methods of freeze concentration (FC), where direct methods had cooling fluids directly in contact with the solution, while indirect methods use a coolant separated from the solution by a wall [480]. FC has been used across wastewater treatment and desalination [480]. In particular, industrial wastewater has seen great uses for incorporating FC into the removal of toxic solvents, dyes, plastics and heavy metals. FC is effective in concentrating industrial wastewater for metal and energy recoveries such as zinc, copper, uranium and nickel (Fig. 10) [291,292]. Unfortunately, high capital costs, tendency to concentrate pollutants, and mechanical complexity bar FC from being widely used [481,482].

3.5.2. Evaporative techniques

Evaporation is done to remove water content and crystallise recoverable solids within the product, and is regarded as a mature technique for crystallising wastewater [481]. This technique is widely used in salt recoveries particularly in zero-liquid discharge systems [481], and can be achieved by lowering the temperature of water, adding solvents or heating [483]. Compressor and distillation systems are used for the treatment of high salinity industrial wastewater [484]. Multiple-effect processes were more cost and performance efficient over single process evaporation [484], however, the presence of other chemicals required more energy to treat the wastewater, but could be offset through the use of renewable energy [276] or more efficient evaporator designs [290]. Beyond salt and water recoveries, dyes, solutes and precious elements can also be recovered by evaporation [276,277] from industrial wastewaters such as shale wastewater that contain large concentrations of lithium, europium, uranium and radium from shale waste streams with possibilities for recovery [485]. The evaporative process relies on the pH, drying agent, and temperature, and for liquids such as urine, requires pH stabilisation (alkalinisation or acidification) before undergoing the evaporative process [486]. However, evaporation, due to the higher latent heat for water, is more energy intensive than FC [486].

4. Discussion

It is clear from the review of a range of resource recovery technologies that multiple product recoveries are possible and should be considered wholly for their applications across urine, sewage, municipal and industrial wastewaters. Materials, nutrients, water, metals and energies are products that can be recovered; however, the emergence of biological, electrochemical, thermal, chemical and membrane-based early-stage technologies are key considerations for designing plants away from removal and disposal practices (Fig. 11). Authors such as Renfrew et al. [5] and Tian et al. [444] took technology selection processes from an economics and investment standpoint, meanwhile, other studies prioritised environmental impacts [17]. Optimal values could be deduced from the combination of social, technical, environmental and economic metrics seen in Iacovidou et al. [487] which also factored in carbon capture and removal of toxins. However, much of the onus on resource CE is on waste management operators like WWTPs [488,489] who end up refining and reselling recovered products, and therefore, technology selection will fall onto WWTP operators given the high transportation costs for urine, sewage sludge and toxic wastewaters.

There continues to be a lack of process frameworks to establish how these emerging technologies could potentially be applied in retrofitting current WWTPs or how they can be utilised within poorer countries. By contrast to OECD countries where the wastewater connectivity rate is more than 90% [490], developing countries will face fewer infrastructural barriers to implementing new and innovative wastewater resource recovery plants, but are hindered from doing so due to priorities on expanding sanitation coverage of WWTPs and lack of funding [491], the reliance on raw material extraction for economic growth and poor government waste management coverage [492]. Resource recovery infrastructure barriers such as these are unsurprising given past experiences with implementing source-separated infrastructures in place to recover P [493], but are highly unlikely to arise from poor

Fig. 10. FC of electroplating wastewater for water purification and heavy metal removal. Taken from [291].

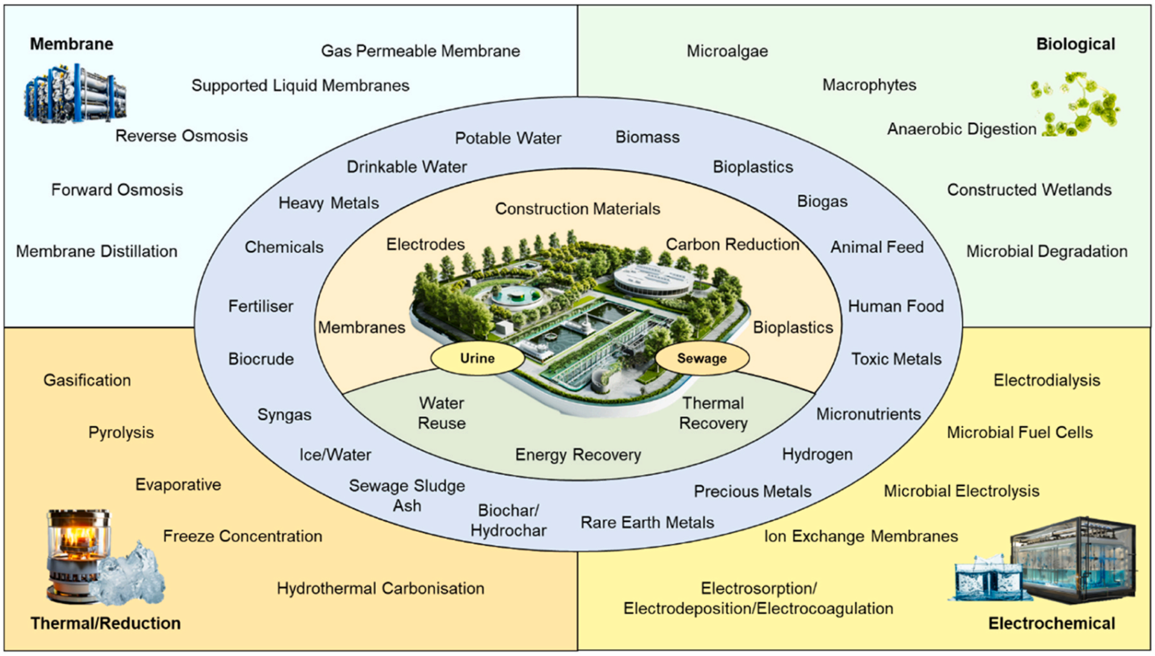

Fig. 11. CE WWTP from a wider perspective. Incorporating a range of products that can also be recovered and used on the WWTP itself such as component and structural replacements, as well as recovered products sold on the market to offset costs.

public acceptance [494]. The question remains on whether to apply retrofitted resource recovery WWTPs or to start from scratch for developing-country WWTP CE. While significant lab research is occurring, the benefits of each wastewater recovery technology remain prone towards siloing. Rhetorically, what should a CE WWTP plant look like when incorporating various emerging resource CE technologies such as MEC, microalgae, AD and ED? Such configurations will highly vary depending on the nature of the wastewater and the costs to run the CE WWTP, yet, remain underexplored due to practical, scalability barriers. CE WWTP technologies, however, expand across different industry applications. For example, electrochemical technologies could precipitate phosphate from both municipal [495] and industrial wastewater [496] and similarly for membrane processes for water recovery (MD [497], FO [498] and RO [499]).

At the heart of resource CE WWTP research are advancements in materials for membranes and electrode development towards efficiency improvements during recovery, extraction and refinement processes. The upscaling of nanomaterials and lab-scale energy recovery systems and their impacts on the commercial scale ingrains uncertainty for plant operators and impedes progress towards wider industry adoption. Furthermore, microalgae bring carbon sequestering benefits which could be of key interest for carbon capture applications. In the case of phosphorous and nitrogen recoveries, ammonia stripping and chemical struvite precipitation continue to dominate membrane nutrient recovery studies achieving high purity grades. Meanwhile, electrochemical technologies known for the robustness for both selectively and broadly recovering metals are beginning to also demonstrate nutrient recovery applications with ED, CDI and EC. Moreover, bioplastics production via PHA and PHB remain largely understudied with microbial and chemical valorisation approaches.

5. Conclusion

This paper identifies the clear and present trends, yet, equally integral importance of industrial and municipal WWTP CE resource recovery technologies. Efforts are made to consider the valuable waste which municipal wastewater generates for nutrient and water recoveries. Meanwhile, industrial wastewater contains many precious metals and even harmful elements that should be recovered for industrial reuse to achieve full circularity. Beyond material, water and nutrient recoveries, energy recoveries and recovery efficiencies play large roles in reducing the operating costs for CE WWTPs. The market resale value of recovered products also contributes strongly to the feasibility of implementing new and novel technologies for commercial upscaling and is more sensitively cost-averse for industrial precious metals. Biological methods appear to demonstrate versatile applications across both these wastewater types, and could potentially bridge gaps between municipal and industrial WWTP CE. Difficulties remain in scaling up biological recovery technologies and reconcentrating biomasses for effective nutrient and energy recoveries.

Then there are the direct recovery of nutrients, water and energy from sewage and urine. These waste streams - particularly the latter - have a strong membrane, biological and volume-reduction focus throughout research. Sewage was highly promising for energy recovery spanning biofuels, biogases and other hydrothermally-derived products. Energy recovery from urine is accomplished through microalgae production of lipids, glucose and biomass which is less energy intensive, but reconcentrating urine-derived microalgae biomass as feedstock for energy production is a challenge. In highly nutritious wastewater streams, biological methods demonstrate high compatibility and sustainability compared to industrial applications, with phytoremediation cited as effective in nutrient extraction, toxin removal and carbon sequestering. This review shows the growing significance biological processes play in the new CE WWTP and its integration with other established and emerging WWTP CE recovery technologies.

CRediT authorship contribution statement

Hokyong Shon: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jungbin Kim:** Writing – review & editing, Investigation, Data curation. **Allan Soo:** Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Data Availability

No data was used for the research described in the article.

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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