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Circular economy from wastewater resource recovery: A review of recent advances and global disparities

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ABSTRACT

Wastewater management has undergone significant evolution from medieval practices, where wastewater was directly discharged into surface water bodies, to modern approaches that emphasise not only treatment for public health but also the recovery of valuable resources. This evolution reflects a shift from unidimensional wastewater treatment, focused solely on health protection, to a multipurpose framework that includes water reclamation, reuse, and resource recovery. This narrative review assesses recent developments in wastewater resource recovery technologies and highlights global disparities in their adoption. By analysing research outputs using relevant keywords such as "Circular Economy", "Wastewater", and "Resource Recovery", the review reveals a significant concentration of research and technological development in the Global North, particularly in Europe and East Asia (mainly China). In contrast, regions like Sub-Saharan Africa (excluding Southern Africa) and parts of Southeast Asia remain largely underserved, hindered by limited infrastructure, inadequate funding, and insufficient institutional support. Key resources recovered from wastewater include nutrients and soil amendments, feed and bioproducts, bioenergy, and metals. Out of 61 studies synthesised and comparatively analysed, 39 % originated from Europe, while none emanated from West and Central Africa, illustrating a stark imbalance in research and innovation. The implications of these disparities are far-reaching. Recommendations for advancing wastewater resource recovery globally were offered, emphasising the importance of inclusive and equitable progress to ensure that no region is left behind in this critical aspect of sustainable development.

1. Introduction

Up until the second half of the 19th century, wastewater treatment was not particularly a priority [1]. It was commonplace to dispose of wastewater directly into surface water bodies, leading to the deterioration of water quality and biotic systems and to water-related morbidities among individuals inhabiting downstream. Subsequently, prioritising wastewater treatment was seen as a prerequisite to enhance public health and ameliorate environmental degradation [2]. This was backed by local and international policies such as the Clean Water Act and World Health Organization drinking-water quality guidelines [3,4]. However, at the beginning of the 21st century, there was an impassioned push to move from the unilateral mechanism of wastewater treatment to incorporate water reclamation and reuse [2,5]. This was due to increased awareness about global challenges like population explosion, unchecked urbanisation, breached planetary boundaries, water scarcity, and increased water demands [5–7]. This push was incorporated as a global target among the United Nations countries via the Millennium Development Goal (MDG) 7, signed in the year 2000, which advocated for environmental sustainability [8]. One of the key metric indicators was a reduction in the proportion of total water resources used. Reclaimed wastewater was mostly reused for agriculture, landscape irrigation, groundwater recharge, nonpotable industrial purposes and, to a limited extent, for drinking purposes [2,7]. However, due to the increased severity of environmental challenges like climate change, unmitigated resource extraction, water scarcity, and food insecurity in

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the last decade, there has been another paradigm shift in wastewater management [9,10]. Besides its reclamation and reuse purposes, wastewater is now broadly regarded as a resource which can be integrated into a circular economy, significantly reducing humans' dependence on natural resource extraction, as shown in Fig. 1. The current goal is to upcycle resources (otherwise regarded as pollutants) like organic carbon, nitrogen, phosphorus, and heavy metals in wastewater and deploy them to productive use [11,12].

In several industrialised societies, wastewater is now considered not only as a water source but also as a nutrient and energy source [13]. In these climes, conventional wastewater treatment plants are being retrofitted to facilitate process alterations and sludge/biomass harvesting for resource recovery [14,15]. This is particularly important because conventional wastewater treatment has a high energy burden, significant environmental footprint, and low resource recovery potential [16]. Wastewater can reportedly generate about 5 folds of the amount of energy required for treatment [13]. The commonly explored technologies are biogas generation via anaerobic sludge digestion, thermal-based technologies like hydrothermal liquefaction, and bioelectrochemical systems [14,17]. Other specific resources that can be recovered are biofertilizers, sludge-derived biochar, biofuels, biopolymers, microbial protein, nutritional bioproducts, metals, volatile fatty acids, carbon dioxide, and extracellular polymeric substances [16–19]. Implementing this circular economy approach to wastewater treatment potentially reduces the associated economic burden and greenhouse gas emissions and limits humans' dependence on crude resource extraction [14,20]. Just like with wastewater reclamation and reuse, a global mandate for concerted efforts to push for universal wastewater resource recovery has been propagated by the 2030 Sustainable Development Goals (SDGs). This mandate is firmly rooted in SDG 6 (Clean Water and Sanitation), which has targets to improve wastewater treatment, reuse, and recycling technologies, giving special support to developing countries [21]. Moreover, the implementation of sustainable wastewater treatment has also been deemed to be germane in achieving other goals like SDGs 3 (Good Health and Well-being), 7 (Affordable and Clean Energy), 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), 13 (Climate Action), 14 (Life Below Water), and 15 (Life on Land) [22].

Even though wastewater is a universal resource, and there are concerted efforts to prioritise sustainable wastewater management globally, current evidence suggests that the achievements so far are predominantly among first-world countries. A similar trend was previously observed where industrialised countries had fully implemented wastewater treatment technologies to substantially mitigate water-related morbidities as far back as the early 20th century, with interest later shifting towards curbing emerging pollutants [23,24]. On the other hand, significant populations in developing countries still struggle with such mundane challenges as conventional wastewater treatment

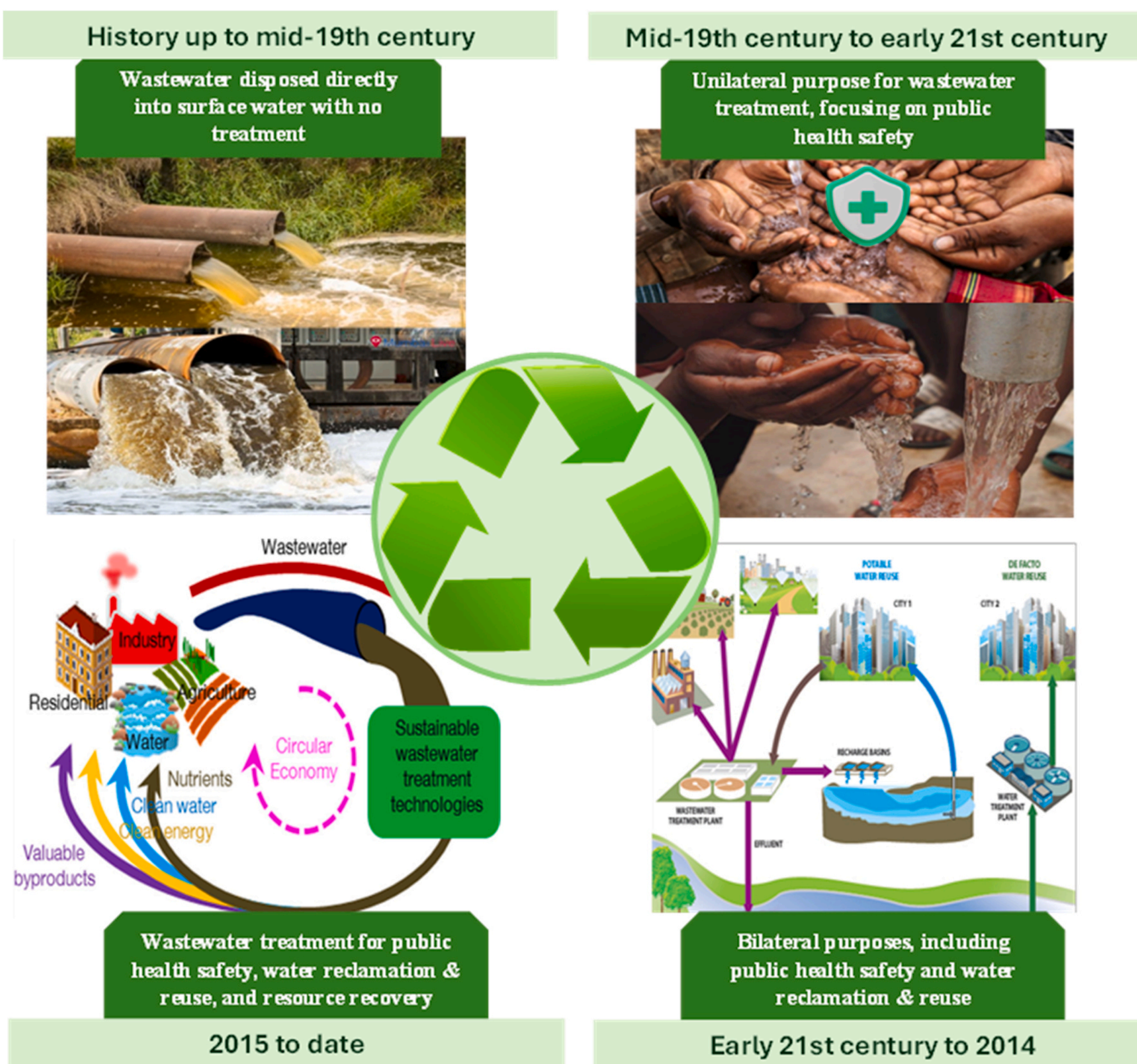

Fig. 1. Wastewater utilisation from the Medieval era to the sustainable development era.

technologies are not as widespread [24–26]. Recent data reveal that over 80 % of wastewater produced globally is disposed of in the environment without sufficient treatment. High-income countries are estimated to treat over two-thirds of wastewater generated, middle-income countries just around one-third, while low-income countries treat under one-tenth of wastewater generated [13]. In a bid to ensure equity in the delivery of the SDGs by 2030, it is pertinent to demystify the existing disparities in sustainable wastewater management. Therefore, this review aims to explore the recent advances in wastewater resource recovery over the past decade across the technological readiness spectrum, depicting the possible inequalities in research, knowledge-sharing, technological advancement, and capacity building across different economies. The effectiveness of current global policies to encourage knowledge sharing and even the spread of technological advancements is also explored. Finally, recommendations are provided on the best ways to reduce disparities and achieve significant gains within the next five years (Target 2030).

2. Advancements in wastewater resource recovery

Before examining specific recovery technologies, it is essential to recognise that wastewater composition varies considerably depending on its source, which fundamentally influences both the selection and efficiency of recovery technologies. Municipal wastewater typically contains 200–600 mg/L biochemical oxygen demand (BOD), 20–50 mg/L total nitrogen (TN), and 5–15 mg/L total phosphorus (TP), making it suitable for nutrient recovery via struvite precipitation or biological processes [27]. In contrast, industrial wastewaters exhibit markedly different characteristics: agro-industrial effluents (e.g., palm oil mill effluent) may contain BOD levels exceeding 25,000 mg/L with high lipid content favouring anaerobic digestion and lipid recovery; textile wastewaters often contain elevated salinity (10–20 g/L NaCl) and synthetic dyes requiring specialised electrochemical or membrane processes; and mining wastewaters are characteristically acidic (pH 2–4) with high metal concentrations (>1000 mg/L) necessitating selective precipitation or biosorption technologies [28]. Furthermore, seasonal and diurnal variations in municipal wastewater with organic loads fluctuating (30–50 %) between peak and off-peak periods demand flexible, adaptive treatment systems. This compositional heterogeneity directly impacts technology selection: high-strength wastewaters (COD >10,000 mg/L) favour energy-positive anaerobic processes, whilst dilute streams require energy-efficient aerobic or hybrid systems [29-31]). Temperature sensitivity further complicates recovery efficiency, as anaerobic digestion rates decrease by approximately 50 % when temperatures drop from 35°C (mesophilic optimum) to 20°C, whilst struvite crystallisation kinetics are relatively temperature-insensitive but highly pH-dependent (optimal pH 8.5–10) [32,33]. Consequently, successful technology deployment requires careful matching of wastewater characteristics to process capabilities, often necessitating pre-treatment (e.g., equalisation, pH adjustment, screening) or multi-stage treatment trains to optimise recovery yields [34].

The field of wastewater resource recovery has witnessed significant advancements, transforming how we perceive and manage wastewater. This paradigm shift is driven by innovative technologies that enable the recovery of essential nutrients, the generation of renewable energy, the production of valuable bioproducts, and the extraction of precious metals. By leveraging associated processes, wastewater treatment systems are evolving into sustainable operations that contribute to the circular economy [35,36]. These advancements not only enhance environmental sustainability and resource efficiency but also offer substantial economic benefits [35]. As wastewater treatment facilities adopt these cutting-edge methods, they play a critical role in achieving global SGDs, addressing environmental challenges, and supporting the transition towards a more sustainable and resilient future. The most common advances in wastewater resource recovery can be subcategorised into nutrients and soil amendments, energy, feeds and bioproducts, and metals. The associated processes are examined below.

Tables 1 and 2, Fig. 2 presents integrated wastewater treatment–recovery flow for four representative wastewater contexts: municipal, high-strength industrial, agricultural/livestock effluent, and decentralised estate systems. Each panel shows where recovery units plug into conventional treatment trains and the resulting products (fertiliser salts, biogas/heat, reusable water, biomass). These systems view clarifies the points of capture for nutrients (N, P), energy, and bioproducts.

2.1. Nutrients and soil amendments

Recovering nutrients from wastewater is essential for sustainable agriculture and environmental protection. Nitrogen and phosphorus are key nutrients targeted for recovery due to their crucial roles in plant growth and their potential to cause eutrophication in water bodies if not managed properly [44]. One prominent method for nutrient recovery is struvite precipitation. Struvite, or magnesium ammonium phosphate, can be precipitated from wastewater and used as a slow-release fertiliser [45,46].

Reaction (Stoichiometric):

$$Mg^{2+} + NH_4+ + PO_4^{3-} + 6H_20 \rightarrow MgNH_4PO_4 \cdot 6H_2O \text{ (Struvite)}$$

This process not only provides a sustainable solution for reducing phosphate loads in water bodies but also offers a valuable agricultural product. Struvite precipitation helps in nutrient recovery by transforming dissolved nutrients into a solid form that can be easily handled and applied to soils [47], as shown in Fig. 3. By mitigating the environmental impact of wastewater discharge, this method addresses both water quality issues and the demand for sustainable fertilisers.

Biosolids, which are treated sewage sludge, represent another valuable product derived from wastewater. Rich in organic matter and nutrients, biosolids are suitable for use as soil amendments [48]. When applied to agricultural fields, biosolids improve soil fertility and structure, enhancing crop yields and promoting sustainable farming practices. The use of biosolids as soil amendments helps close the nutrient loop, recycling essential nutrients back into the soil and reducing the need for synthetic fertilisers [49]. Moreover, biosolids application improves soil health by increasing organic matter content, which enhances soil microbial activity and nutrient availability. High calcium and iron concentrations promote competing precipitates (e.g., hydroxyapatite) that reduce struvite purity; thermal/alkaline pretreatments improve polymer solubilization but increase reagent and energy demand. This includes operational notes on solids retention time (SRT) and dewatering polymer usage as they affect biosolid reuse and polymer recovery efficiencies [38,39].

Biochar, produced from the pyrolysis of biomass including wastewater sludge, is gaining attention as a soil amendment [97,98]. Biochar enhances soil fertility, increases water retention, and sequesters carbon, making it an effective tool for improving soil health and mitigating climate change [50]. The production of biochar from wastewater sludge not only recycles nutrients but also converts waste into a valuable product with multiple environmental benefits [51]. When applied to soils, biochar improves soil structure, reduces nutrient leaching, and enhances the soil's capacity to retain water and nutrient [99,100]. This contributes to long-term soil sustainability and resilience against climate variability.

2.2. Energy

Wastewater contains significant amounts of organic matter that can be converted into various forms of energy, contributing to energy sustainability and reducing reliance on fossil fuels. Advancements in energy recovery from wastewater have led to the development of several

Table 1
Wastewater Resource Recovery Technologies: Performance, energy, costs, TRL, and deployment.

Technology	Principle (Target • Recovery)	Typical operating conditions	Main advantages	Energy input / performance metric	Cost (Band)	TRL	Geographic implementation	Main limitations / scale
Struvite crystallization	Chemical precipitation: $Mg^{2+} + NH_4^+ + PO_4^{3-} \rightarrow MgNH_4PO_4{\cdot}6H_2O$ (Recovers P ± NH_4^+; P recovery 40–80 %.)	pH 8.5–10, Mg:P: N ≈ 1:1:1–1.2, seeding common	Produces slow-release fertilizer, relatively low CAPEX	~0.5–1.5 $kWh{\cdot}m^{-3}$ (dosing/ mixing; plant-specific)	Medium	7–8	US, EU, China, India	Sensitive to Ca^{2+}/ Fe^{3+} interference, needs P > ~30 mg P/L for economic recovery [37,38]
Anaerobic digestion (UASB/AnMBR)	Anaerobic methanogenesis of organics. (Recovers energy as CH_4; VS reduction 40–60 %; 0.20–0.35 m^3 $CH_4{\cdot}kg^{-1}$ VS.)	Mesophilic (35°C) or thermophilic, HRT varies	Mature; high biogas (50–70 % CH_4) (co-digestion increases yield)	Net-producing possible; parasitic loads for mixing/ heating	Meduim-High	8–9	Global	Fouling (AnMBR), dissolution/ fugitive CH_4; needs post-treatment [39].
Microbial fuel cells (BES/MFC)	Exoelectrogenic oxidation → electrons to anode (Recovers electricity; power density ~0.1–2 $W{\cdot}m^{-2}$ lab-typical)	Lab → pilot; internal resistance, small electrode spacing	Direct electricity generation; low-temp operation	Low (mainly pumping); coulombic efficiency varies	Meduim (electrodes drive CAPEX; OPEX low)	4–6	China, EU, US	Low absolute power density; scale-up robustness still a challenge [40].
Hydrothermal liquefaction (HTL)	Thermal conversion of wet sludge → biocrude (Recovers energy as biocrude; ~30–50 % of dry solids)	250–350°C, 10–25 MPa; wet feedstocks tolerated	High energy density product; no dewatering needed	~2.5–4 $kWh{\cdot}kg^{-1}$ DS (order-of-mag.)	High	5–7	US, Japan, EU, Canada	High OPEX; upgrading required; yields vary by feed [41, 42].
Photobioreactors (microalgae)	Photosynthetic nutrient uptake → biomass (Recovers biomass; N,P removal ~50–85 %)	Light-limited; PBR design, hydraulic retention & dilution control	Co-treatment + biomass feedstock	~0.3–0.6 $kWh{\cdot}m^{-3}$ (mix/ harvest)	Low-Medium	5–7	Global	Land/area and harvesting energy constraints; pilot-scale variability [43].

innovative technologies, each with unique benefits and applications [101]. Anaerobic digestion is one of the most well-established processes for converting organic matter in wastewater into energy [55], as shown in Fig. 4. This process occurs in the absence of oxygen, breaking down organic material to produce biogas, a mixture primarily composed of methane and carbon dioxide. Biogas can be utilised for electricity generation, heating, or as vehicle fuel. By harnessing the energy potential of wastewater, anaerobic digestion generates renewable energy and simultaneously reduces the volume of waste, leading to lower disposal costs and a diminished environmental footprint [56]. This process also produces a digestate byproduct, which can be further used as a nutrient-rich soil amendment, thus contributing to a circular economy.

Key formula (biogas methane yield from COD):

- Theoretical methane production per chemical oxygen demand (COD) removed: 0.35 L CH_4/g COD (standard, theoretical upper bound used in engineering estimations). Strait [102]

Worked example:

If a wastewater treatment plant (WWTP) removes 1000 kg COD/day (i.e., 1000,000 g COD/d), the expected CH_4 ≈ 1000,000 × 0.00035 = 350 m^3 CH_4/day (STP). With an electrical conversion efficiency of ~35 % for combined heat and power (CHP) (typical small-scale engines), this corresponds roughly to ~1100 kWh/day usable electricity (350 m^3 × 9.97 kWh/m^3 CH_4 × 0.35 ≈ 1218 kWh; use 9.97 kWh/m^3 as CH_4 energy density) [102,103].

Microbial Fuel Cells (MFCs) represent an emerging and innovative technology that directly converts organic matter into electricity using bacteria [57], as shown in Fig. 5. In MFCs, bacteria oxidise organic compounds present in wastewater, releasing electrons that generate an electrical current [58]. This technology offers a dual benefit: it generates power from wastewater while also treating it. MFCs present a sustainable solution for wastewater treatment facilities aiming to improve their energy efficiency and sustainability. The potential for continuous energy production from organic waste makes MFCs an attractive option for remote or off-grid locations where conventional energy sources may be limited [59]. Typical lab max power densities reported range from mW/m^2 to a few hundred mW/m^2 depending on electrode and substrate (e.g., up to ~100–216 mW/m^2 in recent lab/pilot reports); however, volumetric energy yields remain low (tens of W/m^3 in best lab cases) and scale-up is limited by internal resistance, mass transfer (oxygen at cathode), electrode costs, and hydraulic management. Practical deployment today is for niche, low-power sensors and pilot off-grid sites rather than plant-scale baseload generation [40,104,105].

Thermal processes such as hydrothermal carbonisation and combustion are also employed to convert wastewater sludge into syngas, a mixture of hydrogen, carbon monoxide, and other gases [106,107]. These processes involve the application of heat and pressure to transform organic materials into energy-rich gases. Syngas can be utilised as a renewable energy source, offering an alternative to traditional fossil fuels [60]. The production of syngas from wastewater sludge reduces the environmental footprint of wastewater treatment plants by decreasing the reliance on fossil fuels and lowering greenhouse gas emissions [61]. Additionally, the residual solids from these thermal processes can be further processed into biochar, which has applications as a soil amendment or carbon sequestration agent.

Hydrothermal carbonisation (HTC) is particularly notable for its ability to handle wet waste streams without the need for extensive dewatering, making it an efficient option for processing wastewater sludge [62]. HTC converts organic matter into a coal-like substance called hydrochar, which can be used as a solid fuel or further processed into activated carbon for various industrial applications [63]. This technology not only provides a renewable energy source but also contributes to waste minimisation and resource recovery.

- **HTC yields:** modern HTL pilot studies report biocrude yields in the 20–40 % dry solids mass range and energy yields that can approach net positive energy when co-processing with high-organics feedstocks; note that upgrading to fuel and handling aqueous phase organics are key cost/energy sinks [41].

Table 2
Studies highlighting resource recovery from wastewater under each of the subthemes.

Sub-theme	Wastewater source	Mechanisms/Resources recovered	Reference
Nutrients and Soil Amendments	Municipal and industrial wastewater	Struvite derived from wastewater precipitation supplies fertilizer to the soil.	[44–47]
	Agricultural wastes	Biosolids improve soil structure and fertility.	[48,49]
	Sewage sludge	Biochar derived through pyrolysis of biomass enhances soil fertility, increases water retention, and sequesters carbon.	[50,51]
	Dairy and poultry wastewater	Nutrient recovery through membrane filtration and subsequent use in agriculture. Likewise, the biomass and biodiesel production by *Chlorella* sp. T4	[52,53]
	Textile wastewater	1. The nanofiltration-electrodialysis process effectively extracts dyes, NaCl, and pure water 2. Textile effluent fertilization with biosurfactants can improve soil health and nutrient availability, enhancing crop productivity and agricultural sustainability.	[31,54]
Energy	Municipal wastewater	Biogas is derived from anaerobic digestion for electricity generation, heating, or as a vehicle fuel	[55,56]
	Industrial wastewater	Oxidation of organic compounds in wastewater using bacteria to generate microbial fuel cells (MFC) for electricity.	[57–59]
	Sewage sludge	Syngas an alternative to fossil fuel is generated from hydrothermal carbonization.	[60–63]
	Brewery wastewater	1. Microbial fuel cell technology using locally isolated microorganisms from brewery waste sludge can generate sustainable and clean energy from brewery wastewater, with a removal efficiency of 79β 83 %. 2. Reusing brewery wastewater can be economically viable in 77.2 % of simulated cases, with the strongest dependency on wastewater disposal costs.	[64,65]
	Pulp and paper mill wastewater	Recent advances in lignin removal from pulp and paper mill wastewater, particularly using microorganisms, are eco-friendly, cost-effective, and sustainable, offering the potential for valuable organic material recovery.	[66]
	Agricultural wastewater	Nutrient recovery from wastewater is a sustainable approach, with osmotic membrane bioreactors and bioelectrochemical systems-based hybrid systems being recommended for more economically accessible treatment.	[67]
Feed and Bioproducts	Industrial wastewater from oil and gas	Microorganism cultivation in wastewater to generate biomass rich in protein and lipids	[68–70]
	Agricultural wastewater	Biodegradation of biopolymers by bacteria to generate feedstock to produce polyhydroxyalkanoates	[71,72]
	Industrial wastewater	Algal biomass cultivation for wastewater treatment	[73–76]
	Palm oil mill effluent	Polypropylene micro/nanofiber (PP-MNF) effectively recovers residual oil from palm oil mill effluent, with potential for commercial use due to its reusability and similar oil quality to crude oil.	[77]
	Brewery wastewater	Membrane distillation (MD) offers the highest water recovery (86 %) from pre-treated brewery wastewater, with minimal flux drop and high organics and nutrient rejection.	[78]
	Pulp and paper mill wastewater	Pulp and paper mill sludge can be used as a feedstock for fermentable sugars recovery, mainly glucose, and can be valorized as a feedstock for microbial fermentation to produce value-added products.	[79]
	Agricultural wastewater	Microalgae-based approaches can effectively recover carbon, nitrogen, phosphorus, and other micronutrients from wastewater, improving environmental impacts and promoting a circular economy.	[80]
	Food waste wastewater	1. Lactic acid production through bacterial fermentation for use in bioplastics. 2. Integrated technological routes can maximize resource recovery and sustainable development by treating domestic wastewater with food waste, offering energy, stabilized digest, and improved bioprocess performance.	[81,82]
	Distillery wastewater	Extraction of protein-rich biomass for use as animal feed. Cultivating Chlorella vulgaris in membrane-treated distillery wastewater is feasible, economical, and environmentally friendly, offering an eco-friendly strategy for microalgae biomass production and wastewater reuse.	[83]
Metals	Electronic waste and mining effluent	Biosorption, bioaccumulation, electrochemical recovery, and chemical precipitation are used to recover a wide range of metals including gold (Au), Silver (Ag), and Platinum (Pt) among others.	[84–89]
	Industrial wastewater	The integration of a selective chelating ion exchanger and a solventimpregnated resin can effectively recover rare earth elements from acidic mine waters, making them secondary resources for the clean energy technology industry.	[90,91]
	Mining wastewater	Recovery of copper (Cu) and zinc (Zn) through electrochemical methods and precipitation. The integration of selective precipitation and ion exchange processes showed potential in the separation and recovery of valuable metals from mine waters, promoting a circular economy.	[92]
	Sewage sludge	Recovery of phosphorus and heavy metals through integrated chemical and biological treatment processes. The PULSE process recovers phosphorus from sewage sludge with a maximum leaching efficiency of 65–70 % and removes metals using reactive extraction, resulting in a high-quality product with good plant availability.	[93]
	Acid mine drainage	Recovery of manganese (Mn) and iron (Fe) through biosorption and membrane filtration techniques. Sequential selective precipitation and fluidized bed homogeneous crystallization (FBHC) can recover iron (II) and aluminum (III) from acid mine drainage with efficiencies up to 99.7 % and 99.3 %, respectively.	[94]
	Automobile industry wastewater	Recovery of palladium (Pd) and platinum (Pt) through biosorption and electrochemical processes. Conventional recycling technologies for platinum group metals (PGM) recovery from spent automotive catalysts have shortcomings, but bioprocesses may provide a more sustainable pathway.	[95]
	Textile industry wastewater	Chromium can be removed from wastewater through methods like electrochemical reduction, electrodialysis, and photocatalysis, to avoid environmental pollution and recycle it in the circular economy.	[96]

- **MFC power densities:** report a short range (typical lab 0.1–200 mW/m^2; pilot best cases reported 100–216 mW/m^2 with advanced electrodes), and note volumetric yields (W/m^3) and scale-up constraints.

Overall, the conversion of organic matter in wastewater into energy through anaerobic digestion, MFCs, and thermal processes offers significant environmental and economic benefits. These technologies enhance energy sustainability, reduce reliance on fossil fuels, and lower the environmental impact of wastewater treatment. By integrating these

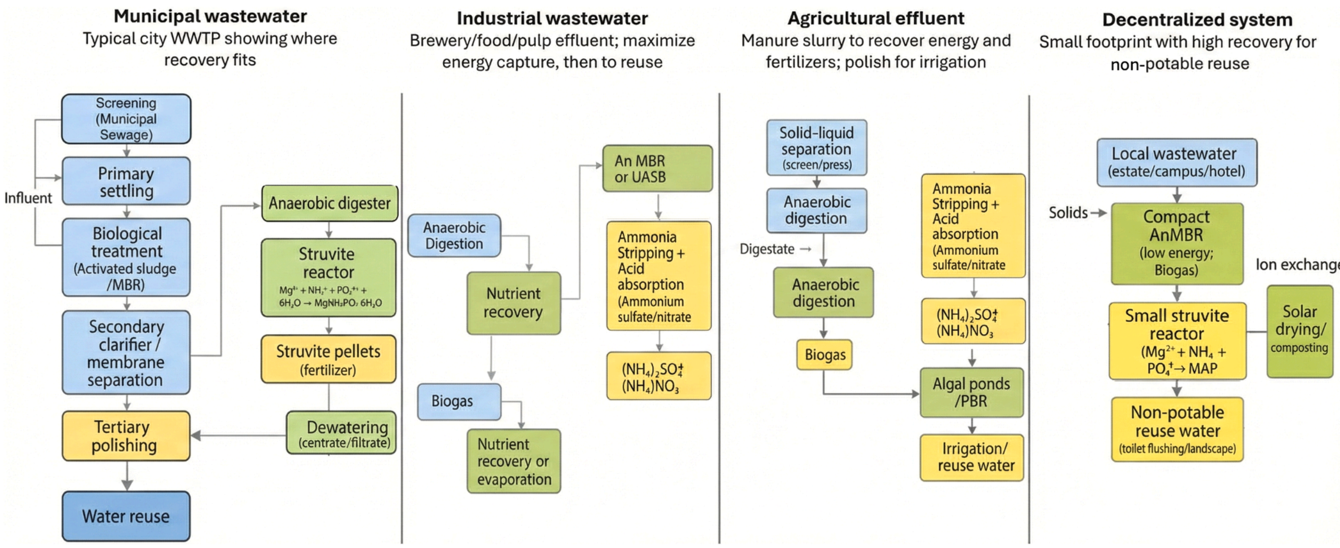

Fig. 2. Integrated wastewater treatment and resource recovery processes for different wastewater types.

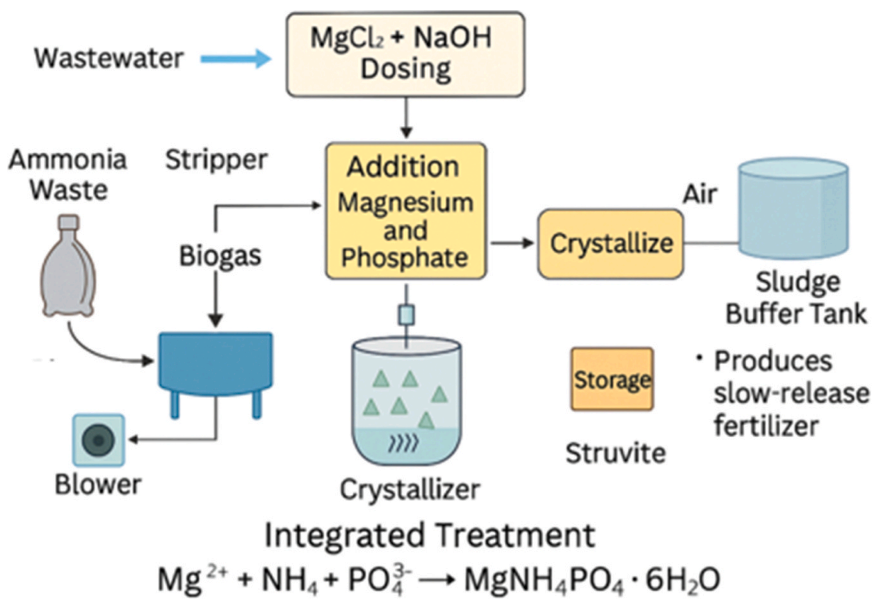

Fig. 3. Schematic of struvite recovery from wastewater showing key steps: ammonia stripping, chemical dosing, crystallisation, and product harvesting. Struvite forms under pH 8.5–10 with Mg:P:N ≈ 1:1:1–1.2, producing a slow-release fertilizer.

energy recovery methods, wastewater treatment facilities can play a crucial role in promoting renewable energy production and supporting a circular economy.

2.3. Feed and bioproducts

The extraction of valuable bioproducts and feedstock from wastewater is increasingly recognised as a sustainable practice with significant environmental and economic benefits. Utilising wastewater as a resource for producing feed and bioproducts not only recycles nutrients but also provides alternative solutions to conventional feedstock, reducing environmental impacts and supporting the circular economy. One innovative approach in this field is the production of Single-cell Protein (SCP). SCP is produced by cultivating microorganisms such as algae, bacteria, and fungi on wastewater substrates. These microorganisms convert the organic matter and nutrients in wastewater into biomass rich in protein, which can be used as high-protein animal feed. This process not only recycles nutrients present in wastewater but also offers a cost-effective and sustainable alternative to traditional animal feeds derived from crops or fishmeal [108–111]. The use of SCP reduces the environmental burden on agricultural systems and contributes to food security by providing an additional protein source for livestock.

Polyhydroxyalkanoates (PHAs) are another significant bioproduct derived from wastewater. PHAs are biodegradable biopolymers produced by certain bacteria that accumulate these polymers as energy storage compounds under nutrient-limiting conditions [71]. Wastewater serves as an excellent feedstock for PHA production due to its rich organic content [112,113]. PHAs can be used to manufacture bioplastics, offering a sustainable solution to plastic pollution. Unlike conventional plastics derived from petrochemicals, PHAs are biodegradable and have minimal environmental impact [72]. By replacing traditional plastics with PHAs in various applications, this technology promotes circular economy principles and reduces the ecological footprint of plastic products.

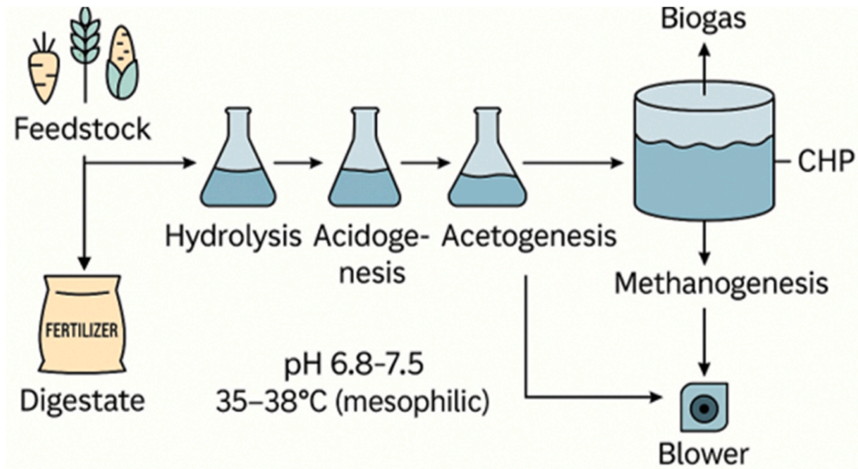

Fig. 4. Schematic of the anaerobic digestion process showing sequential microbial stages converting organic feedstock into biogas and digestate. Operates under mesophilic conditions. Biogas supports energy recovery via CHP; digestate serves as a soil amendment.

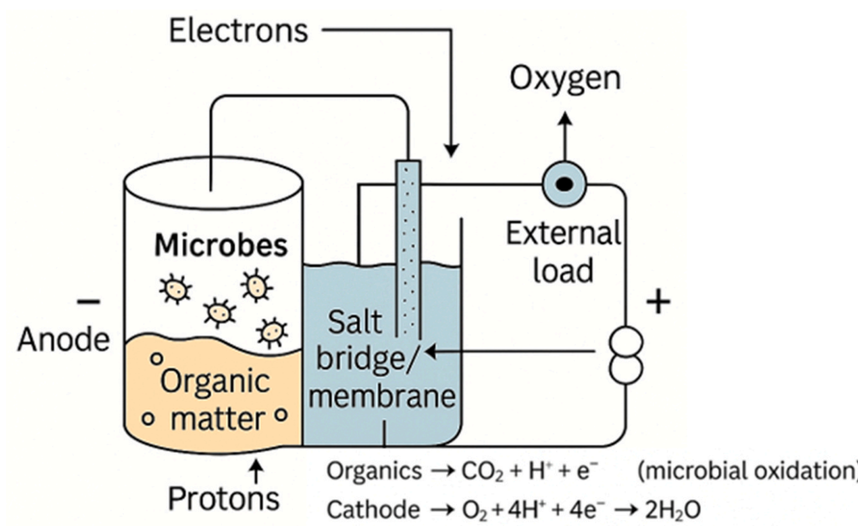

Fig. 5. Schematic of an MFC showing microbial oxidation of organic matter at the anode, electron flow through an external circuit, and proton transfer across a salt bridge to the cathode. The process generates electricity while treating wastewater.

Algal biomass cultivation in wastewater is also gaining momentum as a versatile approach to resource recovery. Algae can be grown in wastewater systems, where they absorb nutrients and organic matter, thus contributing to nutrient removal and wastewater treatment [73]. The harvested algal biomass can be processed into a range of valuable products, including biofuels, animal feed, and other bioproducts. Algal biofuels, such as biodiesel and bioethanol, offer a renewable energy source that can help reduce reliance on fossil fuels [74]. Additionally, algae can be used as a protein-rich feed for livestock and aquaculture, providing a sustainable feed alternative that does not compete with food crops for agricultural land.

The integration of algae-based systems in wastewater treatment enhances overall resource recovery and supports the development of sustainable bioindustries. Algae cultivation systems, such as photobioreactors and open ponds, can be implemented alongside traditional wastewater treatment processes to optimise nutrient recovery and biomass production [75,76]. This symbiotic relationship between wastewater treatment and algae cultivation creates a closed-loop system where waste products are converted into valuable resources, promoting sustainability and efficiency. Besides the macronutrients supplied by the recovered biomass, micronutrients like trace minerals, pigments (e.g. carotenoids) and powerful antioxidants like coenzyme Q10 are also present, offering probiotic effects [114–117]. These significantly enhance plant/animal outcomes.

2.4. Metals

Wastewater often contains various metals that can be recovered and reused, reducing the need for virgin metal extraction and mitigating environmental pollution. The presence of metals in wastewater, including valuable ones such as gold, silver, and platinum, has led to the development of several recovery techniques. These methods not only help in resource conservation but also play a crucial role in reducing the environmental impact associated with metal mining and processing. Biosorption and bioaccumulation techniques utilise specific microorganisms and biosorbents to capture and concentrate metals from wastewater [84]. Certain bacteria, fungi, and algae have a natural affinity for binding metal ions, allowing for efficient extraction of metals from wastewater streams. These biological processes are particularly effective for recovering precious metals like gold, silver, and platinum [85]. Once recovered, these metals can be purified and reused in various industrial processes or for manufacturing new products. The use of biosorption and bioaccumulation is an environmentally friendly approach, leveraging natural biological systems to achieve metal recovery without the need for harsh chemicals or extensive energy inputs.

Biosorption efficiency is commonly described by adsorption-isotherm models that quantify the interaction between metal ions and functional groups on biomass surfaces. The Langmuir isotherm

$$q_e = \frac{q_{\max} K_L C_e}{1 + K_L C_e},$$

assumes monolayer adsorption on a homogeneous surface, while the Freundlich isotherm

$$q_e = K_F C_e^{1/n},$$

accounts for heterogeneous surface binding. Typical maximum adsorption capacities (q_{max}) for biosorbents such as algae, fungi, or activated sludge range between 50 – 250 mg/g, depending on pH (optimal ≈ 5–6), ionic strength, and the presence of competing cations (Ca^{2+}, Mg^{2+}, Na^{+}). Kinetic behaviour often follows a pseudo-second-order rate model, indicating chemisorption as the rate-limiting step. Recent studies emphasise that optimising pH control, biomass pre-treatment, and regeneration cycles significantly enhances metal recovery efficiency and biosorbent longevity [118].

Electrochemical recovery techniques, such as electrocoagulation and electroflotation, involve applying an electric current to wastewater, causing metals to precipitate out of the solution. Electrocoagulation uses electrically induced chemical reactions to destabilise and aggregate metal particles, forming flocs that can be easily separated from the water [86]. Electroflotation, on the other hand, generates tiny gas bubbles that attach to metal particles, lifting them to the surface for removal [87]. These electrochemical methods are highly efficient and can be tailored to target a wide range of metal contaminants. The recovered metals from these processes can be purified and reintroduced into industrial cycles, supporting resource conservation efforts and reducing the need for new metal extraction.

Chemical precipitation is a traditional method that involves adding chemicals to wastewater to precipitate metals, forming insoluble compounds that can then be collected. This method is effective for recovering metals such as copper, zinc, and lead, which are commonly found in industrial wastewater [88]. By adjusting the pH and introducing specific precipitants, metals can be selectively precipitated and separated from the water. Chemical precipitation not only removes harmful metals from wastewater, thus preventing environmental contamination, but also recycles them for further use [89]. This supports sustainable industrial practices by reducing the reliance on virgin raw materials and minimising the environmental footprint of metal processing industries.

Overall, advancements in metal recovery from wastewater are transforming traditional wastewater treatment processes into sustainable systems that generate valuable products. Techniques such as biosorption, electrochemical recovery, and chemical precipitation are integral to this transformation, offering effective and environmentally friendly solutions for metal recovery. These technologies contribute to environmental sustainability by reducing metal pollution and conserving natural resources. Moreover, the economic benefits of recovering and reusing metals align with the principles of the circular economy, maximising resource efficiency and minimising waste. Table 1 highlights some recent studies from each subtheme discussed.

2.5. Emerging approaches in wastewater resource recovery

Emerging wastewater-resource-recovery technologies now span bioelectrochemical systems (BES), photobioreactors (PBRs), hydrothermal liquefaction (HTL), and engineered microbial consortia, each offering distinct recovery pathways yet still constrained by scale, cost and integration challenges. For example, BES such as MFCs have recently been reviewed as promising for both energy generation and nutrient recovery from wastewater, though commercial-scale implementation remains hindered by electrode/material costs, internal resistance and up-scaling issues [119,120]. Photobioreactors using microalgae for N- and P-removal and biomass production are achieving improved pilot yields, but remain limited by light availability, area demands, and seasonal variability. HTL of wet sludge and algal biomass has been techno-economically assessed at full-scale co-located with wastewater-treatment plants, showing favourable energy-return scenarios, yet still challenged by biocrude upgrading, aqueous-phase management, and lower technology readiness [121]. Lastly, advances in engineered microbial consortia promise more resilient, efficient mixed-culture processes for PHA/SCP production and enhanced biofilm performance, but require further work on inoculum cost, reactor control, and real-world stability. Collectively, these approaches mark the frontier of circular wastewater biorefineries, but their translation from pilot to demonstration remains contingent on robust life-cycle analyses, cost models, and integrated system validation.

The transition from laboratory-scale innovation (TRL 3–4) to commercial deployment (TRL 8–9) presents formidable challenges, explaining the geographical concentration of advanced implementations. Scale-up barriers span four domains: (1) Engineering; non-linear mixing efficiency, heat management complications, and materials durability (membrane fouling in AnMBR systems increases disproportionately, with flux declining 20–40 % at full scale); (2) Economic; capital expenditure 2–5 times higher than conventional treatment (MFC electrodes cost £200–500/m² versus £50–100/m² for clarifiers), whilst revenue from recovered products rarely offsets increased costs without subsidies (struvite at £150–300/tonne versus rock phosphate at £50–150/tonne); (3) Process stability; industrial wastewater variability demands advanced real-time monitoring, whilst microbial community stability in biotechnological processes (PHA production, anammox) proves difficult under fluctuating loads; and (4) Regulatory; lack of standardised protocols for recovered product certification and immature markets for novel bio-products [122,123].

Commercial implementation status reveals stark disparities: struvite recovery (TRL 8–9, >100 plants globally in Europe, North America, Japan) and anaerobic digestion (TRL 9, thousands worldwide) have achieved maturity. Conversely, MFCs remain at pilot scale (TRL 5–6, requiring >100 W/m² versus current <2 W/m² for viability), HTL at demonstration scale (TRL 6–7, several USA/Japan/Netherlands facilities), and photobioreactor nutrient recovery (TRL 6–7) faces contamination and seasonal productivity challenges. Advanced implementations concentrate in regions with: (a) strong research infrastructure; (b) supportive policy frameworks (feed-in tariffs, circular economy mandates); (c) established markets for recovered products; and (d) financial capacity to absorb initial costs [124,125].

2.6. Economic feasibility and cost–performance implications of wastewater resource recovery

The economic viability of wastewater resource recovery depends significantly on technology choice, market value of recovered products, and site-specific operating conditions. Techno-economic assessments show that the valorisation of biosolids into fertilisers can be financially attractive. For instance, Hassan et al. [126] evaluated three biosolids management systems in Russia and demonstrated that windrow composting (WC), tunnel composting (TC), and lime stabilisation (LS) can generate 29,785–35,056 m³ of biofertilizers annually from 22,000 m³ of sewage sludge. However, profitability conditions require biofertilizer pricing of €19/m³ for WC and LS and €77/m³ for TC, with discounted payback periods of 3.1 years (WC), 18.1 years (LS), and 25.3 years (TC) and a 10 % internal rate of return (IRR) [126]. Similarly, co-combustion of municipal sewage sludge with agricultural biomass has been shown to reduce heat recovery cost to €19–30/MWh, compared to €29–66/MWh for mono-combustion, due to improved heating value and reduced energy demand [127]. Yet, these systems remain highly sensitive to fertiliser and energy market prices, and in some cases require sewage sludge gate fee subsidies to achieve positive profit margins.

Nutrient recovery solutions also demonstrate promising economic potential but remain dependent on chemical consumption and product pricing. Mayor et al. [128] reported that a pilot nutrient recovery train (struvite crystallisation + ion exchange + membrane contactor) yields a negative NPV due to high chemical usage (up to 30 % of gross cost). However, profitability becomes achievable if struvite and ammonium nitrate prices rise to €0.58/kg and €0.68/kg, respectively, values plausible under global fertiliser price volatility [128]. Meanwhile, novel urine valorisation systems demonstrate accelerated cost recovery. For instance, Wu et al. [129] found that a decentralised Na-chabazite and biochar adsorption approach for fresh urine achieved 89 % N and 99 % P recovery, and achieved break-even within 21 years, outperforming centralised alternatives due to lower capital investment and better product-market alignment. Sensitivity analysis revealed that just a 20 % increase in product selling price or urine inflow substantially boosts IRR [129], highlighting the importance of robust value chains for recovered fertilisers.

Energy-focused strategies often offer the strongest near-term economic justification. Lugo et al. [130] showed that an algae-based forward osmosis + seawater reverse osmosis system achieved a lower cost of potable reuse water ($\$1.97/m^3$) compared to the conventional advanced treatment benchmark ($\$2.03/m^3$), benefiting from integrated bioenergy and nutrient recovery pathways. Likewise, co-digestion of waste activated sludge with food waste demonstrated considerable returns: a South African pilot study showed that 20–40 % co-digestion can offset 94–196 % of WWTP electricity demand, saving $2.0–2.3 million per year, with payback < 1 year, positive NPV, and IRR surpassing the discount rate [131]. Thermochemical approaches for sludge management also show high upside, for example, fast pyrolysis bio-oil can reach $0.10/kg market value, and gasification can yield > $3.5 million benefit over landfilling [132]. With policy instruments such as carbon pricing (e.g. €20/t CO_2-eq) and biochar incentives [133], profitability increases substantially due to long-term sequestration and soil enhancement benefits.

3. Disparities in wastewater resource recovery research and technological advancements

3.1. Disparities in technological advancements

Since the implementation of the Sustainable Development Goals in 2015, the study and development of wastewater resource recovery technologies have become increasingly vital. This field focuses on converting wastewater into valuable resources, including energy, fertilisers, and other bioproducts [134]. However, despite global initiatives, significant disparities exist in the progress and utilisation of these technologies, particularly between advanced and developing nations.

In the Global North, Europe and North America lead the way in research and technological advancements for wastewater resource recovery. Countries like Germany, Denmark, and the Netherlands have made considerable progress by upgrading wastewater treatment facilities to incorporate resource recovery methods [135,136]. These enhanced facilities prioritise the extraction of essential resources such as phosphorus, methane, and bioenergy. Notably, the "Nutrient Platform" initiative in the Netherlands has played a crucial role in promoting phosphorus recovery technology [137]. Significant advancements have been reported in this area, particularly in Germany and the Netherlands, where large-scale phosphorus recovery systems have been successfully implemented due to strict regulations and substantial incentives for recycling [138]. The European Union's Horizon 2020 research and innovation program has further supported numerous projects focused on resource recovery from wastewater. One such initiative, the SMART-Plant project, aims to demonstrate innovative treatment methods for extracting valuable resources like biopolymers and nutrients [139].

In North America, the United States and Canada have made notable contributions to wastewater resource recovery. The U.S. Environmental Protection Agency (EPA) has provided substantial funding for research into anaerobic digestion systems, which convert organic materials in wastewater into biogas [140]. Advancements in co-digestion methods, which enhance biogas production and energy retrieval, have been extensively documented [141]. Additionally, the U.S. Department of Energy has supported projects that link academic research with industrial implementation, fostering progress in bioenergy recovery from wastewater. There are challenges posed by infrastructure costs and regulatory barriers but incentives and improved co-digestion practices could significantly boost sustainable energy production [142]. Significant advancements in bioenergy and bioplastic recovery technologies have also been observed in both the United States and Canada [143,144].

The success of these regions in integrating circular economy principles into wastewater management can be attributed to robust institutional support, substantial financial resources, and advanced technological expertise. The effective retrofitting of wastewater treatment plants in these countries serves as an exemplar for sustainable wastewater management. Conversely, the Global South, including Sub-Saharan Africa, Southeast Asia, and parts of Latin America, has experienced slower progress in technological advancement. In most of these countries, domestic wastewater is directly discharged into surface water bodies without any form of treatment [145], while existing treatment plants further deteriorate and decline due to increased pressure from population growth [146]. While there are commendable pilot programs in these regions, such as nutrient recovery efforts in South Africa and bioenergy recovery initiatives in Brazil, these projects tend to be limited in scope and impact compared to those in the Global North [147]. Sub-Saharan Africa, in particular, faces significant challenges in adopting advanced wastewater resource recovery technologies, primarily due to limited financial resources and a shortage of skilled professionals [148]. In these regions, pilot plants often serve as experimental facilities, with the transition from pilot projects to full-scale implementation being slow and difficult [149]. The absence of a comprehensive legal framework further exacerbates these challenges, making it difficult to replicate the progress seen in more affluent countries. Additionally, funding and government interest in wastewater resource recovery are generally lower in these countries as they grapple with more pressing economic and environmental issues.

In Southeast Asia, research on biomass recovery from wastewater has shown growth, but it is primarily concentrated in countries with well-established research infrastructures, such as Malaysia and Thailand. For instance, a study assessed the viability of extracting biomass from palm oil mill effluent (POME) in Malaysia [150]. Their study not only demonstrated the feasibility of this process but also underscored the need for further research to improve its efficiency across the region. They also explored alternative approaches, such as POME eradication, to enhance sustainability within the palm oil industry. Meanwhile, Brazil has made significant strides in bioenergy recovery from wastewater within Latin America. Another study evaluated the viability of two anaerobic digestion methods, Upflow Anaerobic Sludge Blanket (UASB) and activated sludge processing systems (ASPS) [151]. Their findings showed that both methods are technically and economically feasible, with positive Net Present Values (NPVs) of 5.88 million Rands (MR$) and 9.02 million Rands (MR$), respectively, and Internal Rates of Return (IRRs) of 17.1 %. Additionally, substituting grid electricity with biogas resulted in a substantial reduction in greenhouse gas emissions. However, scaling these technologies for broader applications remains challenging due to financial and regulatory constraints. Table 3 provides a comprehensive summary of some of the wastewater resource recovery technologies that have reached Technological Readiness Level (TRL) 5 or higher in these regions.

The situation is particularly dire in Sub-Saharan Africa, where the implementation of advanced wastewater technologies is almost non-

Table 3
Summary of some wastewater resource recovery technologies at TRL 5 and above.

Technology	Wastewater Type	Resource Recovered	Location of Study	Technological Readiness Level	Results Obtained	References
Struvite Precipitation for Phosphorus Recovery	Synthetic and Real Wastewater	Phosphorus (as struvite crystals)	Laboratory Setting (Assessment also on real wastewater from Portugal)	TRL 5 (Technology validated in a relevant environment)	Minimum 30 mg P/L required for precipitation; Mg/P molar ratio of 1 enhances P removal efficiency. Coexisting ions like calcium reduce purity of struvite, but seeding with biomass ash improves P removal and pH control. Final struvite purity in wastewater was low (15 %wt).	[38]
Upflow Anaerobic Sludge Blanket (UASB) Reactors	Municipal Wastewater	Biogas (CH4, CO2, H2S)	South of Brazil	TRL 6 (Technology demonstrated in relevant environment)	Mean sewage flow: 345 ± 120 L/s; Organic load removal: 48 %; Biogas composition: 82.32 % CH_4, 2.66 % CO_2, 3453 H_2S; Estimated electric power generation: 3118.6 kWh/d (130 KW installed power). Time behavior of removed organic load and biogas flow exhibited variability, periodicity, and nonstationary behavior.	[152]
Upflow Anaerobic Sludge Blanket (UASB) Reactors	Domestic Sewage	Biogas, Sludge	Paraná, Brazil	TRL 6 (Technology demonstrated in relevant environment)	The study assessed 239 STPs in Paraná, Brazil, and found that biogas, as the primary by-product, could meet the energy demands of a city with 111,000 inhabitants. Biogas accounted for 65 %, 64 %, and 74 % of total energy potential in small, medium, and large STPs, respectively. Despite its potential, only 0.4 % is currently exploited.	[153]
Anaerobic/Anoxic/Aerobic Membrane Bioreactor (MBR) with MgCO3-based Pellets	Municipal Wastewater	Phosphorus	Muddy Creek WWTP (Cincinnati, OH, USA)	TRL 5 (Laboratory scale demonstration in relevant environment)	Achieved 91.6 % P recovery from municipal wastewater using the MBR system with $MgCO_3$ pellets and ethanol. Maximum P adsorption capacity was 12.8 mg P/g $MgCO_3$.	[154]
Integrated Bioprocesses (Anaerobic Digestion + Tertiary Treatment)	Palm Oil Mill Effluent (POME)	Biogas, Biofertilizer, Recycled Water	Malaysian Palm Oil Mills	TRL 6 (System/subsystem model or prototype demonstration in a relevant environment)	Potential to achieve zero-effluent discharge with BOD < 20 mg/L. This approach could produce biogas, biofertilizer, and recycled water, thus transforming POME into high-value-added products while meeting stringent environmental regulations.	[155]
Aluminium-Based Water Treatment Sludge (WTS) as Adsorption Medium	Electroplating Wastewater	Heavy Metals (Cu, Cr, Pb, Zn, Co, Hg)	Bhandup water treatment plant, Mumbai, India	TRL 6 (System/subsystem model or prototype demonstration in a relevant environment)	Batch tests showed effective removal of Cu, Pb, Zn at higher pH; Cr (VI) removal was less effective at higher pH. Column tests with real wastewater demonstrated complete Cu removal up to 100 bed volumes, with Cr removal ranging from 78 to 92 %. Cu (II) and Cr (VI) sorption capacities were 1.7 mg/g and 3.5 mg/g, respectively.	[156]
SeMPAC (Sequential Batch Reactor with External Submerged Microfiltration Membrane)	Hospital Wastewater (HWW)	Treated Water (with reduced Organic Micropollutants)	NW of Spain	TRL 6 (System/subsystem model or prototype demonstration in a relevant environment)	The integrated pilot plant demonstrated effective removal of organic micropollutants (OMPs) including recalcitrant compounds like carbamazepine after PAC (Powdered Activated Carbon) addition. Long sludge retention times and high biomass concentrations enhanced OMP biotransformation.	[157]
Anaerobic Membrane Bioreactor (AnMBR)	Industrial and Municipal Wastewater	Methane, Hydrogen, Ethanol, Nutrients (for reuse, e.g., algae production)	Poland	TRL 6 (System/subsystem model or prototype demonstration in a relevant environment)	The technology demonstrated complete biomass retention, efficient organic matter degradation for energy production, and nutrient concentration for reclamation. Challenges include membrane fouling and methane dissolution in permeate.	[158]

existent. While there are some advancements at a pilot scale in countries like South Africa and Malaysia, as seen in Table 3, the broader region remains largely underserved. Most of Sub-Saharan Africa still lacks the infrastructure and institutional support needed to develop and sustain these technologies, further widening the disparity between the Global North and South in terms of wastewater resource recovery. Many areas are still struggling with fundamental challenges like access to basic water, sanitation, and hygiene (WASH), and wastewater treatment practices are minimal at best [145,159–161]. This has left the region lagging behind significantly.

3.2. Disparities in wastewater resource recovery research output

Besides technological advancements, the discrepancy in research productivity is also notable. For technological progress to be realised, robust research from academic institutions and research institutes is essential worldwide. However, a significant disparity exists in the distribution of research efforts. When searching for research articles (laboratory-based) on Scopus and Google Scholar databases from 2020 onward using a combination of the keywords "Circular economy," "Wastewater," and "Resource recovery," it becomes apparent that most of the research is conducted by scholars from Europe. A study explored the integration of circular economy principles into wastewater treatment processes in Europe and underscored the effective collaboration between academic institutions and industry in advancing bioenergy recovery technologies, such as converting wastewater sludge into biogas [162]. These regions exhibit a high level of academic-industrial cooperation, which drives innovation and facilitates efficient technology adoption.

Analysis of 61 studies (Table A1, supplementary material) reveals stark geographical concentration. Europe dominated with 24 studies (39 %) spanning phosphorus recovery (Italy, Spain), nutrient platforms (Netherlands), and circular economy frameworks (Germany, Denmark, Austria). East Asia, predominantly China, contributed 8 studies (13 %) on electrochemical recovery, microalgae systems, and implementation challenges [163,164]. North America (5 studies, 8 %) emphasised life cycle assessments and anaerobic digestion optimization, whilst Southern Africa (5 studies, 8 %) addressed rural sanitation transitions. South Asia (5 studies, 8 %) from India and Pakistan covered water treatment sludge and wastewater-to-energy systems. Latin America (4 studies, 7 %) focused on Brazilian frameworks and Mexican bioenergy, Southeast Asia (4 studies, 7 %) on palm oil mill effluent treatment, Middle East (3 studies, 5 %) on water-scarce contexts and phototropic bacteria, and Oceania (3 studies, 5 %) on Australian photobioreactor demonstrations. Critically, not a single study originated from West or Central Africa, underscoring the profound research capacity gap in these regions [123]. This imbalance in research productivity further exacerbates the region's challenges in advancing wastewater resource recovery technologies. Fig. 6 illustrates a summary of the geographical distribution of these studies, while a detailed summary of each paper is provided in Table A1 supplementary file. These findings highlight the urgent need for increased research efforts and technological investments in regions like SSA, where basic infrastructure and institutional support remain critically underdeveloped.

4. Implications and future recommendations

As we progress through the sustainable development era, it is crucial to recognise that the world operates as an interconnected system where environmental degradation in one region inevitably impacts others. This reality is evident in the global repercussions of climate change, where regions with minimal carbon footprints, such as small island nations, bear the brunt of its consequences. Similarly, in the sphere of wastewater resource recovery, it is imperative that no region is left behind in technological advancements. Developing countries, particularly in Sub-Saharan Africa and Southeast Asia, face significant challenges, but they also present unique opportunities. These regions are still in the early stages of waste management infrastructure development, which could make it easier to implement advanced resource recovery technologies without the need for extensive overhauls of existing systems.

International organisations like the United Nations (UN), the United Nations Development Programme (UNDP), and the World Bank play critical roles as global stakeholders in this field. However, their efforts must go beyond mere involvement; they must actively hold member states accountable for meeting sustainability goals, particularly in wastewater management and resource recovery. The following recommendations are essential to ensure that technological advancements are inclusive and globally impactful:

1. Establish Knowledge Exchange Platforms with Technical Capacity Building Components: Facilitating regular exchanges between foreign experts and institutions in SSA and other developing regions can significantly accelerate the adoption of advanced wastewater resource recovery technologies. Specifically, these platforms should include: (a) structured technology transfer programmes pairing developed-country institutions with regional universities for co-supervised doctoral research on locally-adapted systems; (b) secondment schemes enabling 6–12 month placements of operators and engineers in operational facilities (Europe, North America, East Asia) for hands-on training in process control and troubleshooting; (c) regional demonstration hubs showcasing 3–5 proven technologies (e.g., UASB reactors for tropical climates, low-maintenance struvite systems) with replication support; and (d) virtual knowledge networks sharing standard operating procedures, troubleshooting guides, and performance benchmarking data across geographical boundaries. Professors and technical personnel from technologically advanced countries should be encouraged to engage in knowledge transfer initiatives, conducting workshops, training programmes, and collaborative research with local institutions. These platforms can foster innovation and provide the technical know-how required to implement and sustain new technologies.

2. Improve Access to Research Publications with Emphasis on Open Science: The cost of publishing and accessing academic research is a significant barrier for researchers in developing countries. To democratise knowledge effectively: (a) major funding bodies (European Commission, US NSF, UKRI) should mandate open-access publication

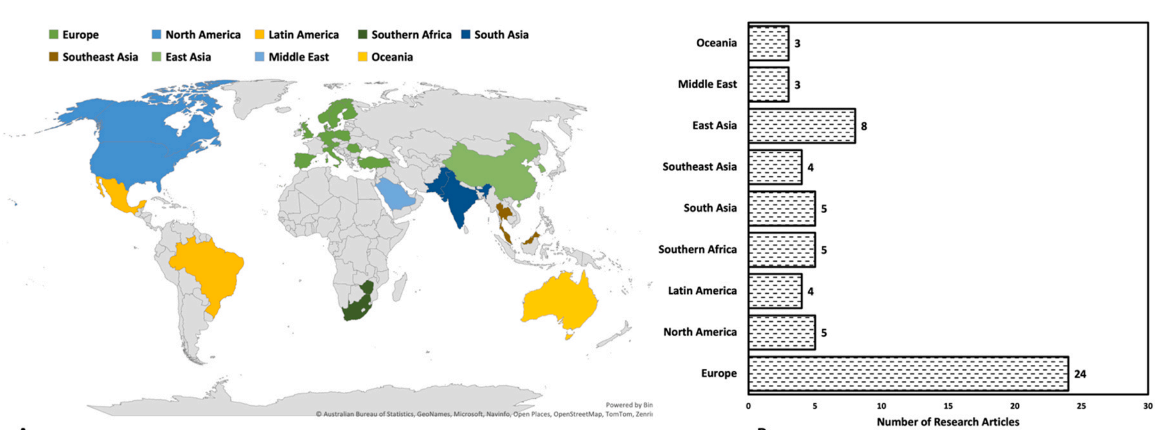

Fig. 6. Recent publications on wastewater resource recovery across the world highlighting prevalent disparities.

for wastewater research, with "diamond open access" (no fees) for low-income country researchers; (b) establish a dedicated international fund (£10–15 million annually) waiving article processing charges for developing country researchers in high-impact journals; (c) develop regional repositories for grey literature, technical reports, and operational data containing invaluable practical insights; and (d) translate key technical guidance and standards into major regional languages (French, Spanish, Portuguese, Hindi, Swahili) for non-English-speaking practitioners. To democratise knowledge and foster global collaboration, it is essential to reduce or subsidise publication fees and provide open access to research on wastewater resource recovery. International bodies and academic publishers should consider waiving fees for researchers from low-income regions or creating dedicated funds to support their participation in global scientific discourse.

3. Design Tailored Grants for Locally-Adapted Technology Development and Validation: Funding is a critical factor in accelerating technological advancements in wastewater resource recovery. Grant programmes should specifically: (a) prioritise "appropriate technology" approaches optimised for local constraints (e.g., low-energy nutrient recovery for off-grid contexts, simple struvite systems requiring minimal inputs); (b) support pilot-to-demonstration scale projects (TRL 5–7) with £ 500,000–2 million funding for 3-year demonstrations including techno-economic assessment and operator training; (c) mandate 40–50 % local engineers and scientists in project teams to ensure knowledge retention; (d) allocate 15–20 % of budgets to monitoring, evaluation, and open-access dissemination; and (e) establish regional challenge funds (£5–10 million) incentivising solutions for specific challenges (e.g., high-salinity textile wastewaters, monsoonal flow variations). International grant programs should be tailored to support projects that address local challenges and contexts. By prioritising grants that focus on innovative, locally-adapted solutions, we can encourage the development of technologies that are both effective and economically viable in the regions where they are most needed.

4. Engage Multinational Corporations Through Enhanced Corporate Social Responsibility and Regulatory Mechanisms: Multinational companies operating in developing countries generate substantial waste, making them key players in the implementation of circular economy (CE) approaches. Engagement should encompass: (a) mandatory resource recovery targets for industrial dischargers, for instance, requiring facilities generating $> 1000\ m^3$ /day wastewater to implement at least one resource recovery pathway (biogas, nutrient recycling, water reuse) within 5 years, with escalating discharge fees for non-compliance; (b) structured partnerships with regional universities whereby industries co-fund applied research positions (e.g., industrial PhD programmes) tackling specific wastewater treatment challenges, ensuring research relevance whilst building local capacity; (c) technology transfer agreements where multinational corporations operating wastewater treatment systems in-country commit to training local engineers and gradually transitioning operation to local firms, preventing perpetual dependency on foreign expertise; and (d) creation of industry consortia (similar to the Water Environment Federation's industrial programmes) focused on sector-specific resource recovery (e.g., textile wastewater in South Asia, agro-industrial effluents in Southeast Asia) that share best practices, jointly procure equipment to reduce costs, and collectively invest in research. These corporations should be incentivised or mandated to incorporate wastewater resource recovery into their CSR strategies. Collaborating with local universities and research institutions can not only help these companies manage their own waste more sustainably but also contribute to broader technological advancements in the region.

5. Strengthen Accountability in International Aid with Technical Conditionalities: International organisations like the UN, UNDP, and the World Bank must hold governments accountable for their commitments to sustainability targets, particularly in the area of wastewater management. Accountability mechanisms should include: (a) specific, measurable targets in loan conditionalities (e.g., 30 % nutrient recovery from centralised plants by 2030, 50 % biogas retrofits by 2032); (b) biannual independent audits with transparent findings informing disbursement schedules; (c) linking debt relief to demonstrated progress in circular wastewater infrastructure; (d) establishing a "Global Wastewater Resource Recovery Fund" (£500 million–1 billion) providing concessional financing (2–3 % interest, 20-year terms) for retrofits and greenfield facilities in low- and lower-middle-income countries; and (e) embedding technical assistance (design expertise, procurement support, operational training) within lending arrangements to maximise success rates. Before approving loans or aid packages, these institutions should require concrete action plans and timelines for achieving specific goals in wastewater resource recovery. This approach will ensure that financial support is directly tied to measurable progress in environmental sustainability.

6. Foster Development and Validation of Locally-Appropriate, Low-Cost Technologies: One of the key challenges in wastewater biotechnology research is the high cost of developing and implementing new technologies. Targeted technical approaches include: (a) simplified struvite recovery using locally-available magnesium sources (seawater, crushed dolomite/magnesite) rather than imported reagents, reducing operating costs 40–60 %; (b) passive anaerobic systems (baffled reactors, constructed wetlands with biogas capture) for small communities (<5000 population equivalent) where activated sludge is uneconomical; (c) solar-driven technologies, solar-thermal enhancement of anaerobic digestion in tropical regions (improving rates 20–35 %) or solar-powered membrane distillation for arid climates; (d) modular resource recovery units (10–100 m^3/day) manufactured using local materials and skills, enabling distributed deployment; and (e) locally-abundant biomaterials for biosorption (agricultural residues for metal recovery, crustacean shells for phosphorus precipitation). However, by focusing on locally derived solutions, these costs can be significantly reduced. Research and development should prioritise technologies that are adapted to the local environment, resources, and economic conditions. Such an approach not only makes these technologies more affordable but also ensures that they are more likely to be adopted and maintained by local communities.

7. Develop Context-Specific Technical Standards and Certification Frameworks: A critical barrier to technology adoption in developing regions is the lack of locally-relevant standards and certification processes. Technical recommendations include: (a) establishing regional technical working groups (e.g., African Water Association, Asian Development Bank) to develop standards balancing environmental protection with economic feasibility, pragmatic biosolids guidelines for local agriculture rather than unattainable EU/US standards; (b) creating tiered certification schemes (Class A/B/C) enabling market development whilst managing risks proportionately; (c) developing simplified, low-cost testing protocols executable by national agencies without expensive equipment (field-test kits for nutrients, portable XRF for heavy metals versus ICP-MS); and (d) harmonising standards within regional economic communities (ECOWAS, ASEAN, SADC) to facilitate technology transfer and trade.

8. Implement Graduated Policy Support Mechanisms Aligned with Technology Readiness Levels: Policy interventions should be stage-appropriate: (a) early-stage technologies (TRL 3–5): competitive research grants and innovation prizes (£100,000–500,000); (b) demonstration-stage (TRL 6–7): de-risking instruments including loan guarantees, first-loss capital, or public procurement commitments; (c) near-commercial (TRL 7–8): feed-in tariffs for biogas/electricity, tax incentives (VAT exemptions for struvite), or mandatory blending (10 % phosphorus from recovered sources by 2030); and (d) mature technologies (TRL 8–9): regulatory mainstreaming embedding resource recovery in discharge permits as integral components, not optional extras.

In conclusion, addressing global disparities in wastewater resource recovery is not just a matter of technological advancement but also of equity and sustainability. The technical path forward requires simultaneous progress on multiple fronts: advancing fundamental research;

validating technologies for diverse wastewater compositions and contexts; building human and institutional capacity through sustained investment in education and knowledge exchange; creating enabling policy and market environments rewarding circular approaches; and mobilising blended finance combining public, philanthropic, and private capital. Success demands coordination across research institutions, technology vendors, utilities, regulators, development organisations, and local communities, united by recognition that sustainable wastewater management represents strategic investment in environmental resilience, resource security, and economic opportunity, not burdensome cost. By implementing these recommendations, we can foster a more inclusive approach to environmental stewardship, ensuring that all regions, particularly those in the Global South, have the tools and support needed to contribute to and benefit from the circular economy. The window for action is narrow: achieving SDG 6 targets by 2030 requires accelerating current progress rates by factors of 3–5 in many developing regions, an ambitious but achievable goal if recommendations outlined herein are implemented systematically, adequately resourced, and sustained beyond short-term project cycles.

CRediT authorship contribution statement

Ojima Z. Wada: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Visualization, Conceptualization. **Abimbola O. Ige:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Visualization. **Bamise I. Egbewole:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **David B. Olawade:** Writing – review & editing, Writing – original draft, Project Administration, Methodology, Investigation.

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Consent to participate

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Appendix A. Supporting information

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Data availability

Data will be made available on request.

References

[1] W. Udo, C. In Su, D. Eva-Maria, Fundamentals of biological wastewater treatment, Wiley-VCH, 2006. ⟨https://application.wiley-vch.de/books/sample/3527312196_c01.pdf⟩.
[2] G. Tchobanoglous, B. Franklin, S. David. Wastewater engineering: treatment and reuse, fourth ed., McGraw-Hill Education, New York, 2004.
[3] WHO (2009) *WHO guidelines for drinking-water quality*. Geneva. Available at: ⟨https://apps.who.int/iris/bitstream/handle/10665/70050/WHO_HSE_WSH_09.05_eng.pdf⟩ (Accessed 12 April 2023).
[4] J. Worley, M. Wilson, Manure/effluent management: systems design and government regulations. Encyclopedia of Dairy Sciences, Elsevier, 2011, pp. 392–398, https://doi.org/10.1016/B978-0-12-374407-4.00298-3.
[5] A.N. Angelakis, T. Asano, A. Bahri, B.E. Jimenez, G. Tchobanoglous, Water reuse: from ancient to modern times and the future, Front. Environ. Sci. 6 (2018), https://doi.org/10.3389/fenvs.2018.00026.
[6] W. Steffen, K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, et al., Planetary boundaries: guiding human development on a changing planet, Science 347 (2015), https://doi.org/10.1126/science.1259855.
[7] V. Lazarova, T. Asano, A. Bahri, J. Anderson, Milestones in water reuse: the best success stories, IWA Publishing, 2013, https://doi.org/10.2166/9781780400716.
[8] WHO (2018) *Millennium Development Goals (MDGs)*. WHO Fact Sheets. Available at: ⟨https://www.who.int/news-room/fact-sheets/detail/millennium-development-goals-(mdgs)⟩ (Accessed 13 April 2023).
[9] C.M. Galanakis, The future of food, Foods 13 (2024) 506, https://doi.org/10.3390/foods13040506.
[10] V. Singh, Water resources. in Textbook of Environment and Ecology, Springer Nature Singapore, Singapore, 2024, pp. 107–122, https://doi.org/10.1007/978-981-99-8846-4_7.
[11] H.G. Castellanos, Y. Aryanfar, H. Fardinnia, B. Arslan, M. Ilbas, A. Keçebaş, Characterization and utilization of industrial wastewater in biorefinery systems: a comprehensive approach, Environ. Prog. Sustain. Energy 43 (2024), https://doi.org/10.1002/ep.14399.
[12] A. Christou, V.G. Beretsou, I.C. Iakovides, P. Karaolia, C. Michael, T. Benmarhnia, et al., Sustainable wastewater reuse for agriculture', Nat. Rev. Earth Environ. 5 (2024) 504–521, https://doi.org/10.1038/s43017-024-00560-y.
[13] M. Diamanti, Infrastructure Solutions: no wastewater to waste, Eur. Invest. Bank Infrastruct. Solut. (2022). Available at: ⟨https://www.eib.org/en/essays/wastewater-resource-recovery⟩.
[14] X. Tian, R.E. Richardson, J.W. Tester, J.L. Lozano, F. You, Retrofitting municipal wastewater treatment facilities toward a greener and circular economy by virtue of resource recovery: techno-economic analysis and life cycle assessment, ACS Sustain. Chem. Eng. 8 (2020) 13823–13837, https://doi.org/10.1021/acssuschemeng.0c05189.
[15] S. Kwon, C. Zhang, J. Oh, K. Park, Sustainability assessment of retrofitting alternatives for large and old wastewater treatment plants in Seoul, Water Sci. Technol. 87 (2023) 969–986, https://doi.org/10.2166/wst.2023.036.
[16] P. Kehrein, M. van Loosdrecht, P. Osseweijer, M. Garfí, J. Dewulf, J. Posada, A critical review of resource recovery from municipal wastewater treatment plants: market supply potentials, technologies and bottlenecks, Environ. Sci. Water Res. Technol. 6 (2020) 877–910, https://doi.org/10.1039/C9EW00905A.
[17] D. Puyol, D. Bastone, T. Hülsen, S. Astals, M. Peces, J.O. Krömer, Resource recovery from wastewater by biological technologies: opportunities, challenges, and prospects, Front. Microbiol. 7 (2017), https://doi.org/10.3389/fmicb.2016.02106.
[18] Wada, A.S. Vincent, H.R. Mackey, -cell protein production from purple non-sulphur bacteria-based wastewater treatment, Rev. Environ. Sci. Biotechnol. (2022), https://doi.org/10.1007/s11157-022-09635-y.
[19] S. Zuhara, S. Pradhan, M. Pasha, G. McKay, Potential of GTL-derived biosolids for water treatment: fractionization, leachate, and environmental risk analysis, Water 14 (2022) 4016, https://doi.org/10.3390/w14244016.
[20] K. Gurung, W.Z. Tang, M. Sillanpää, Unit energy consumption as benchmark to select energy positive retrofitting strategies for Finnish wastewater treatment plants (WWTPs): a case study of Mikkeli WWTP, Environ. Process. 5 (2018) 667–681, https://doi.org/10.1007/s40710-018-0310-y.
[21] United Nations (2023) *Envision2030: 17 goals to transform the world for persons with disabilities*. Available at: ⟨https://www.un.org/development/desa/disabilities/envision2030.html⟩ (Accessed 16 April 2023).
[22] Rodriguez, D.J., Serrano, H.A., Delgado, A., Nolasco, D. & Saltiel, G. (2020) *From waste to resource: shifting paradigms for smarter wastewater interventions in Latin America and the Caribbean*. Available at: ⟨www.worldbank.org⟩.
[23] E.J. Tiedeken, A. Tahar, B. McHugh, N.J. Rowan, Monitoring, sources, receptors, and control measures for three European Union watch list substances of emerging concern in receiving waters: a 20-year systematic review, Sci. Total Environ. 574 (2017) 1140–1163, https://doi.org/10.1016/j.scitotenv.2016.09.084.
[24] G. Lofrano, J. Brown, Wastewater management through the ages: a history of mankind, Sci. Total Environ. 408 (2010) 5254–5264, https://doi.org/10.1016/j.scitotenv.2010.07.062.
[25] O.Z. Wada, D.B. Olawade, Recent occurrence of pharmaceuticals in freshwater, emerging treatment technologies, and future considerations: a review, Chemosphere 374 (2025) 144153, https://doi.org/10.1016/j.chemosphere.2025.144153.
[26] A. Gallego-Schmid, R.R.Z. Tarpani, Life cycle assessment of wastewater treatment in developing countries: a review, Water Res. 153 (2019) 63–79, https://doi.org/10.1016/j.watres.2019.01.010.

[27] Y. Leng, A. Soares, Microbial phosphorus removal and recovery by struvite biomineralisation in comparison to chemical struvite precipitation in municipal wastewater, J. Environ. Chem. Eng. 11 (2) (2023) 109208.
[28] C.C. Yap, A.D.A.B.A. Sofian, Y.J. Chan, S.K. Loh, M.F. Chong, L.K. Lim, High organic loading rate treatment of palm oil mill effluent using a pilot-scale integrated anaerobic-aerobic bioreactor: a comprehensive performance study, Fuel 382 (2025) 133727.
[29] Lotha, T.N. & Jamir, L. (n.d.) 'Advanced biomass strategies for aerobic and anaerobic treatment systems: insights from practical applications', in Aerobic and Anaerobic Microbial Treatment of Industrial Wastewater, pp. 186–213. CRC Press.
[30] N. Twi-Yeboah, D. Osei, W.H. Dontoh, G.A. Asamoah, J. Baffoe, M.K. Danquah, Enhancing energy efficiency and resource recovery in wastewater treatment plants, Energies 17 (13) (2024) 3060.
[31] R.P. Singh, B.R. Glick, D. Rathore, Role of textile effluent fertilization with biosurfactant to sustain soil quality and nutrient availability, J. Environ. Manag. 268 (2020) 110664.
[32] V.B. Aguilar-Pozo, J. Chimenos, B. Elduayen-Echave, K. Olaciregui-Arizmendi, A. López, J. Gómez, M. Guembe, I. García, E. Ayesa, S. Astals, Struvite precipitation in wastewater treatment plants anaerobic digestion supernatants using a magnesium oxide by-product, Sci. Total Environ. 890 (2023) 164084.
[33] C. González-Morales, B. Fernández, F.J. Molina, D. Naranjo-Fernández, A. Matamoros-Veloza, M.A. Camargo-Valero, Influence of pH and temperature on struvite purity and recovery from anaerobic digestate, Sustainability 13 (19) (2021) 10730.
[34] H. Wu, C. Vaneeckhaute, Nutrient recovery from wastewater: a review on the integrated physicochemical technologies of ammonia stripping, adsorption and struvite precipitation, Chem. Eng. J. 433 (2022) 133664.
[35] J. Campos, A. Mosquera-Corral, Á. Río, A. Pedrouso, Sustainable wastewater management and treatment, Sustainability (2022), https://doi.org/10.3390/su14159137.
[36] U. Ghimire, G. Sarpong, V. Gude, Transitioning wastewater treatment plants toward circular economy and energy sustainability, ACS Omega 6 (2021) 11794–11803, https://doi.org/10.1021/acsomega.0c05827.
[37] B. Tansel, G. Lunn, O. Monje, Struvite formation and decomposition characteristics for ammonia and phosphorus recovery: a review of magnesium-ammonia-phosphate interactions, Chemosphere 194 (2017) 504–517, https://doi.org/10.1016/j.chemosphere.2017.12.004.
[38] A.F. Santos, L.S. Mendes, P. Alvarenga, L.M. Gando-Ferreira, M.J. Quina, Nutrient recovery via struvite precipitation from wastewater treatment plants: influence of operating parameters, coexisting ions, and seeding, Water 16 (12) (2024) 1675.
[39] M. Lenzuni, A. Converti, A.A. Casazza, From laboratory- to industrial-scale plants: future of anaerobic digestion of olive mill solid wastes, Bioresour. Technol. 394 (2024) 130317.
[40] J. Wang, K. Ren, Y. Zhu, J. Huang, S. Liu, A review of recent advances in microbial fuel cells: preparation, operation, and application, BioTech 11 (4) (2022) 44.
[41] Z. Wang, X. Li, H. Liu, C.S.K. Lin, Q. Wang, Hydrothermal liquefaction of sewage sludge: a comprehensive review of biocrude oil production, byproducts valorization, and future perspectives, Renew. Sustain. Energy Rev. 224 (2025) 116086.
[42] J.D. Watkins, A. Kumar, P.J. ValdezWhole algae hydrothermal liquefaction and upgrading: a review of progress and challenges and insight into the future.
[43] S.A. Razzak, K. Bahar, K.O. Islam, A.K. Haniffa, M.O. Faruque, S.Z. Hossain, M. M. Hossain, Microalgae cultivation in photobioreactors: sustainable solutions for a greener future, Green. Chem. Eng. 5 (4) (2024) 418–439.
[44] Y. Nancharaiah, S. Mohan, P. Lens, Recent advances in nutrient removal and recovery in biological and bioelectrochemical systems, Bioresour. Technol. 215 (2016) 173–185, https://doi.org/10.1016/j.biortech.2016.03.129.
[45] R. Kumar, P. Pal, Assessing the feasibility of N and P recovery by struvite precipitation from nutrient-rich wastewater: a review, Environ. Sci. Pollut. Res. 22 (2015) 17453–17464, https://doi.org/10.1007/s11356-015-5450-2.
[46] Y. Wang, J. Mou, X. Liu, J. Chang, Phosphorus recovery from wastewater by struvite in response to initial nutrients concentration and nitrogen/phosphorus molar ratio, Sci. Total Environ. 789 (2021) 147970, https://doi.org/10.1016/j.scitotenv.2021.147970.
[47] A. Siciliano, C. Limonti, G. Curcio, R. Molinari, Advances in struvite precipitation technologies for nutrients removal and recovery from aqueous waste and wastewater, Sustainability 12 (2020) 7538, https://doi.org/10.3390/su12187538.
[48] B. Sharma, A. Sarkar, P. Singh, R. Singh, Agricultural utilization of biosolids: a review on potential effects on soil and plant growth, Waste Manag. 64 (2017) 117–132, https://doi.org/10.1016/j.wasman.2017.03.002.
[49] C. Roman-Perez, G. Hernandez-Ramirez, Nitrous oxide production and nitrogen transformations in a soil amended with biosolids, Can. J. Soil Sci. 102 (2021) 505–518, https://doi.org/10.1139/CJSS-2021-0064.
[50] Z. Elkhlifi, J. Iftikhar, M. Sarraf, B. Ali, M. Saleem, I. Ibranshahib, M. Bispo, L. Meili, S. Ercişli, E. Kayabasi, N. Ansari, A. Hegedűsová, Z. Chen, Potential role of biochar on capturing soil nutrients, carbon sequestration and managing environmental challenges: a review, Sustainability (2023), https://doi.org/10.3390/su15032527.
[51] A. Gopinath, G. Divyapriya, V. Srivastava, A. Laiju, P. Nidheesh, M. Kumar, Conversion of sewage sludge into biochar: a potential resource in water and wastewater treatment, Environ. Res. (2020) 110656, https://doi.org/10.1016/j.envres.2020.110656.
[52] S.F.T. Gumbi, T. Mutanda, A.O. Olaniran, Nutrient removal from dairy and poultry wastewater with simultaneous biomass and biodiesel production by *Chlorella* sp. T4 isolated from a freshwater stream in South Africa, Waste Biomass.. Valoriz. 12 (2021) 6931–6943.
[53] N. Pang, A.D. Bergeron, X. Gu, X.-J. Fu, T. Dong, Y. Yao, S. Chen, Recycling of nutrients from dairy wastewater by extremophilic microalgae with high ammonia tolerance, Environ. Sci. Technol. (2020).
[54] J. Lin, Q. Chen, X. Huang, Z. Yan, X. Lin, W. Ye, S. Arcadio, P. Luis, J. Bi, B. Van der Bruggen, S. Zhao, Integrated loose nanofiltration–electrodialysis process for sustainable resource extraction from high-salinity textile wastewater, J. Hazard. Mater. 419 (2021) 126505.
[55] S. Saha, B. Basak, J. Hwang, E. Salama, P. Chatterjee, B. Jeon, Microbial symbiosis: a network towards biomethanation, Trends Microbiol. 28 (12) (2020) 968–984, https://doi.org/10.1016/j.tim.2020.03.012.
[56] M. Uddin, S. Siddiki, M. Mofijur, F. Djavanroodi, M. Hazrat, P. Show, S. Ahmed, Y. Chu, Prospects of bioenergy production from organic waste using anaerobic digestion technology: a mini review, Front. Energy Res. 9 (2021), https://doi.org/10.3389/fenrg.2021.627093.
[57] I. Rodrigues, V. Leão, Producing electrical energy in microbial fuel cells based on sulphate reduction: a review, Environ. Sci. Pollut. Res. (2020) 1–10, https://doi.org/10.1007/s11356-020-09728-7.
[58] H. Gul, W. Raza, J. Lee, M. Azam, M. Ashraf, K. Kim, Progress in microbial fuel cell technology for wastewater treatment and energy harvesting, Chemosphere 281 (2021) 130828, https://doi.org/10.1016/j.chemosphere.2021.130828.
[59] W. Tan, S. Chong, H. Fang, K. Pan, M. Mohamad, J. Lim, T. Tiong, Y. Chan, C. Huang, T. Yang, Microbial fuel cell technology: a critical review on scale-up issues, Processes (2021), https://doi.org/10.3390/pr9060985.
[60] G. Tonial, P. Paraíso, L. Jorge, Assessment of biogas and syngas production from sugarcane vinasse: a sustainable alternative for the production of renewable fuels, Environ. Prog. Sustain. Energy (2023), https://doi.org/10.1002/ep.14294.
[61] A. Callegari, A. Capodaglio, Properties and beneficial uses of (bio)chars, with special attention to products from sewage sludge pyrolysis, Resources 7 (2018) 20, https://doi.org/10.3390/resources7010020.
[62] R. Khoshbouy, F. Takahashi, K. Yoshikawa, Preparation of high surface area sludge-based activated hydrochar via hydrothermal carbonization and application in the removal of basic dye, Environ. Res. 175 (2019) 457–467, https://doi.org/10.1016/j.envres.2019.04.002.
[63] Y. Shen, A review on hydrothermal carbonization of biomass and plastic wastes to energy products, Biomass. Bioenergy (2020), https://doi.org/10.1016/j.biombioe.2020.105479.
[64] M. Verhuelsdonk, K. Glas, H. Parlar, Economic evaluation of the reuse of brewery wastewater, J. Environ. Manag. 281 (2020) 111804.
[65] L.W. Negassa, M. Mohiuddin, G.A. Tiruye, Treatment of brewery industrial wastewater and generation of sustainable bioelectricity by microbial fuel cell inoculated with locally isolated microorganisms, J. Water Process Eng. 41 (2021) 102018.
[66] I. Haq, P. Mazumder, A.S. Kalamdhad, Recent advances in removal of lignin from paper industry wastewater and its industrial applications: a review, Bioresour. Technol. (2020) 123636.
[67] Y. Ye, H.H. Ngo, W. Guo, S.W. Chang, D.D. Nguyen, X. Zhang, J. Zhang, S. Liang, Nutrient recovery from wastewater: from technology to economy, Bioresour. Technol. Rep. 11 (2020) 100425.
[68] O.Z. Wada, M. Alherbawi, T. Al-Ansari, G. McKay, H.R. Mackey, Purple nonsulfur bacteria biomass as a potential biofuel source: a study of lipid characterization methods using gas chromatography, Biofuels Bioprod. Bioref. (2025), https://doi.org/10.1002/bbb.2743.
[69] O.Z. Wada, M. Pasha, A.S. Vincent, G. McKay, H.R. Mackey, Dim lights, bright prospects: purple phototrophic bacteria-driven industrial wastewater treatment for biomass resource recovery at low light intensities', Process Saf. Environ. Prot. 194 (2025) 1067–1080, https://doi.org/10.1016/j.psep.2024.12.037.
[70] O.Z. Wada, A.S. Vincent, G. McKay, H.R. Mackey, Harnessing pH and light cycles to boost microbial protein production in mixed culture purple non-sulfur bacteria wastewater bioremediation, J. Water Process Eng. 69 (2025) 106785, https://doi.org/10.1016/j.jwpe.2024.106785.
[71] C. Velázquez-Sánchez, G. Espín, C. Peña, D. Segura, The modification of regulatory circuits involved in the control of polyhydroxyalkanoates metabolism to improve their production, Front. Bioeng. Biotechnol. 8 (2020).
[72] S. Bassi, A. Boldrin, G. Frenna, T. Astrup, 'An environmental and economic assessment of bioplastic from urban biowaste: the example of polyhydroxyalkanoate', Bioresour. Technol. 327 (2021) 124813 https://doi.org/10.1016/j.biortech.2021.124813.
[73] S. Priyadharshini, P. Babu, S. Manikandan, R. Subbaiya, M. Govarthanan, N. Karmegam, Phycoremediation of wastewater for pollutant removal: a green approach to environmental protection and long-term remediation, Environ. Pollut. 290 (2021) 117989, https://doi.org/10.1016/j.envpol.2021.117989.
[74] K. Soni, P. Maurya, S. Singh, Algae-based biofuels: hope for future energy, J. Med. Plants Stud. (2023), https://doi.org/10.22271/plants.2023.v11.i4a.1569.
[75] N. Renuka, S. Ratha, F. Kader, I. Rawat, F. Bux, Insights into the potential impact of algae-mediated wastewater beneficiation for the circular bioeconomy: a global perspective, J. Environ. Manag. 297 (2021) 113257, https://doi.org/10.1016/j.jenvman.2021.113257.
[76] L. Vargas-Estrada, A. Longoria, P. Okoye, P. Sebastian, Energy and nutrients recovery from wastewater cultivated microalgae: assessment of the impact of wastewater dilution on biogas yield, Bioresour. Technol. 341 (2021) 125755, https://doi.org/10.1016/j.biortech.2021.125755.

[77] V. Semilin, J. Janaun, C.H. Chung, D. Touhami, S.K. Haywood, K.P. Chong, A. Z. Yaser, S.H. Zein, Recovery of oil from palm oil mill effluent using polypropylene micro/nanofiber, J. Hazard. Mater. 404 (2020) 124144.
[78] N. Anwar, M.S. Rahaman, Membrane desalination processes for water recovery from pre-treated brewery wastewater: performance and fouling, Sep. Purif. Technol. 252 (2020) 117420.
[79] J.E. Naicker, R. Govinden, P. Lekha, B.B. Sithole, Transformation of pulp and paper mill sludge (PPMS) into a glucose-rich hydrolysate using green chemistry: assessing pretreatment methods for enhanced hydrolysis, J. Environ. Manag. 270 (2020) 110914.
[80] D. Nagarajan, D.-J. Lee, C.Y. Chen, J.S. Chang, Resource recovery from wastewaters using microalgae-based approaches: a circular bioeconomy perspective, Bioresour. Technol. (2020) 122817.
[81] L. Song, D.-F. Yang, R. Liu, S. Liu, X. Dai, The dissolution of polysaccharides and amino acids enhanced lactic acid production from household food waste during pretreatment process, Sci. Total Environ. 864 (2022) 161068.
[82] A.S. Giwa, M. Sheng, X. Zhang, Y. Wu, H. Bo, A.G. Memon, S. Bai, N.K.M. Ali, J. M. Ndungutse, W. Kaijun, Approaches for treating domestic wastewater with food waste and recovery of potential resources, Environ. Pollut. Bioavailab. 34 (2022) 501–517.
[83] F. Li, D.K. Amenorfenyo, Y. Zhang, N. Zhang, C. Li, X. Huang, Cultivation of *Chlorella vulgaris* in membrane-treated industrial distillery wastewater: growth and wastewater treatment, Front. Environ. Sci. (2021).
[84] A. Ghomi, N. Asasian-Kolur, S. Sharifian, A. Golnaraghi, Biosorption for sustainable recovery of precious metals from wastewater, J. Environ. Chem. Eng. 8 (2020) 103996, https://doi.org/10.1016/j.jece.2020.103996.
[85] A. Adeeyo, O. Bello, O. Agboola, R. Adeeyo, J. Oyetade, M. Alabi, J. Edokpayi, R. Makungo, Recovery of precious metals from processed wastewater: conventional techniques nexus advanced and pragmatic alternatives, Water Reuse (2023), https://doi.org/10.2166/wrd.2023.068.
[86] M. Moradi, Y. Vasseghian, H. Arabzade, A. Khaneghah, Various wastewaters treatment by sono-electrocoagulation process: a comprehensive review of operational parameters and future outlook, Chemosphere 263 (2021) 128314, https://doi.org/10.1016/j.chemosphere.2020.128314.
[87] R. Mohtashami, J. Shang, Electroflotation for treatment of industrial wastewaters: a focused review, Environ. Process. (2019) 1–29, https://doi.org/10.1007/s40710-019-00348-z.
[88] M. Benalia, L. Youcef, M. Bouaziz, S. Achour, H. Menasra, Removal of heavy metals from industrial wastewater by chemical precipitation: mechanisms and sludge characterization, Arab. J. Sci. Eng. 47 (2021) 5587–5599, https://doi.org/10.1007/s13369-021-05525-7.
[89] R. Shrestha, S. Ban, S. Devkota, S. Sharma, R. Joshi, A. Tiwari, H. Kim, M. Joshi, Technological trends in heavy metals removal from industrial wastewater: a review, J. Environ. Chem. Eng. 9 (2021) 105688, https://doi.org/10.1016/j.jece.2021.105688.
[90] M. Hermassi, M. Granados, C. Valderrama, C. Ayora, J.L. Cortina, Recovery of rare earth elements from acidic mine waters by integration of a selective chelating ion-exchanger and a solvent impregnated resin, J. Environ. Chem. Eng. 9 (2021) 105906.
[91] F. Nkinahamira, A. Alsbaiee, Q. Zeng, Y. Li, Y. Zhang, M. Feng, C.-P. Yu, Q. Sun, Selective and fast recovery of rare earth elements from industrial wastewater by porous β-cyclodextrin and magnetic β-cyclodextrin polymers, Water Res. 181 (2020) 115857.
[92] X. Vecino, M. Reig, J. López, C. Valderrama, J.L. Cortina, Valorisation options for Zn and Cu recovery from metal influenced acid mine waters through selective precipitation and ion-exchange processes: promotion of on-site/off-site management options', J. Environ. Manag. 283 (2021) 112004.
[93] Z.A. Shariff, L. Fraikin, A. Bogdan, A. Léonard, E. Meers, A. Pfennig, PULSE process: recovery of phosphorus from dried sewage sludge and removal of metals by solvent extraction, Environ. Technol. 45 (2023) 2820–2832.
[94] V.G. Le, T.-D.-H. Vo, B.-S. Nguyen, C.T. Vu, Y.-J. Shih, Y.H. Huang, Recovery of iron(II) and aluminum(III) from acid mine drainage by sequential selective precipitation and fluidized bed homogeneous crystallization (FBHC), J. Taiwan Inst. Chem. Eng. 115 (2020) 135–143.
[95] S. Karim, Y.P. Ting, Recycling pathways for platinum group metals from spent automotive catalyst: a review on conventional approaches and bio-processes, Resour. Conserv. Recycl. (2021).
[96] H. Peng, J. Guo, Removal of chromium from wastewater by membrane filtration, chemical precipitation, ion exchange, adsorption, electrocoagulation, electrochemical reduction, electrodialysis, electrodeionization, photocatalysis and nanotechnology: a review, Environ. Chem. Lett. 18 (2020) 2055–2068.
[97] S. Pradhan, H.R. Mackey, T.A. Al-Ansari, G. McKay, Biochar from food waste: a sustainable amendment to reduce water stress and improve the growth of chickpea plants, Biomass.. Convers. Biorefinery 12 (2022) 4549–4562, https://doi.org/10.1007/s13399-022-02575-1.
[98] S. Pradhan, P. Parthasarathy, H.R. Mackey, T. Al-Ansari, G. McKay, Effect of pistachio shell biochar and organic cow manure application on plant growth, water retention capacity and nutrient stress mitigation, Waste Biomass.. Valoriz. 16 (2025) 761–772, https://doi.org/10.1007/s12649-024-02681-3.
[99] S. Pradhan, A.H. Abdelaal, K. Mroue, T. Al-Ansari, H.R. Mackey, G. McKay, Biochar from vegetable wastes: agro-environmental characterization, Biochar 2 (2020) 439–453, https://doi.org/10.1007/s42773-020-00069-9.
[100] S. Pradhan, F.Z. Lahlou, I. Ghiat, H. Bilal, G. McKay, T. Al-Ansari, A comprehensive decision-making approach for the application of biochar in agriculture to enhance water security: a GIS-AHP based approach, Environ. Technol. Innov. 36 (2024) 103801, https://doi.org/10.1016/j.eti.2024.103801.
[101] A. Capodaglio, G. Olsson, Energy issues in sustainable urban wastewater management: use, demand reduction and recovery in the urban water cycle, Sustainability (2019), https://doi.org/10.3390/su12010266.
[102] Strait, J. (2019) Co-digestion: biogas production & digester capacity calculations. Available at: 〈https://cswea.org/docs/Codigestion-Biogas-Production-Digester-Capacity-June-2019.pdf〉.
[103] F. Sher, N. Smječanin, H. Hrnjić, A. Karadža, R. Omanović, E. Šehović, J. Sulejmanović, Emerging technologies for biogas production: a critical review on recent progress, challenges and future perspectives, Process Saf. Environ. Prot. 188 (2024) 834–859.
[104] T.C. Dakal, N. Singh, A. Kaur, P.K. Dhillon, J. Bhatankar, R. Meena, R.K. Sharma, B. Gadi, B.S. Sahu, A. Patel, New horizons in microbial fuel cell technology: applications, challenges, and prospects, Biotechnol. Biofuels Bioprod. 18 (1) (2025) 79.
[105] N. Bazina, T.G. Ahmed, M. Almdaaf, S. Jibia, M. Sarker, Power generation from wastewater using microbial fuel cells: a review, J. Biotechnol. 374 (2023) 17–30.
[106] S. Mariyam, M. Alherbawi, G. McKay, T. Al-Ansari, Converting waste into sustainable aviation fuel (SAF): a systematic literature review, Renew. Sustain. Energy Rev. 226 (2026) 116380, https://doi.org/10.1016/j.rser.2025.116380.
[107] S. Mariyam, M. Shahbaz, T. Al-Ansari, H.R. Mackey, G. McKay, A critical review on co-gasification and co-pyrolysis for gas production, Renew. Sustain. Energy Rev. 161 (2022) 112349, https://doi.org/10.1016/j.rser.2022.112349.
[108] O.Z. Wada, U. Onwusogh, A.S. Vincent, G. McKay, H.R. Mackey, Valorization of purple non-sulfur bacteria biomass from anaerobic treatment of fuel synthesis process wastewater to microbial protein: a means of enhancing food security in arid climates, Biomass.. Convers. Biorefinery (2023), https://doi.org/10.1007/s13399-023-04518-w.
[109] O.Z. Wada, A. Vincent, G. McKay, H.R. Mackey, Converting fuel-synthesis process water to aquaculture feed by purple non-sulfur bacteria, Chem. Eng. Technol. (2023), https://doi.org/10.1002/ceat.202200535.
[110] J. Delamare-Deboutteville, D.J. Batstone, M. Kawasaki, S. Stegman, M. Salini, S. Tabrett, et al., Mixed culture purple phototrophic bacteria is an effective fishmeal replacement in aquaculture, Water Res. X 4 (2019) 100031, https://doi.org/10.1016/j.wroa.2019.100031.
[111] E.D. Macusi, M.A. Cayacay, E.Q. Borazon, A.C. Sales, A. Habib, N. Fadli, et al., Protein fishmeal replacement in aquaculture: a systematic review and implications on growth and adoption viability, Sustainability 15 (2023) 12500, https://doi.org/10.3390/su151612500.
[112] R. Shaikh, N. Rashid, G. McKay, H.R. Mackey, Photobioreactor design for polyhydroxyalkanoate production using anoxygenic photoheterotrophs: a review, Fermentation 9 (2023) 778, https://doi.org/10.3390/fermentation9080778.
[113] S. Shaikh, N. Rashid, G. McKay, H.R. Mackey, Resource recovery through bioremediation of fuel-synthesis wastewater in a biofilm photobioreactor using purple non-sulfur bacteria: a circular bioeconomy approach, Chem. Eng. J. Adv. 19 (2024) 100614, https://doi.org/10.1016/j.ceja.2024.100614.
[114] O.Z. Wada, N. Rashid, P. Wijten, P. Thornalley, G. McKay, H.R. Mackey, Evaluation of cell disruption methods for protein and coenzyme Q10 quantification in purple non-sulfur bacteria, Front. Microbiol. 15 (2024), https://doi.org/10.3389/fmicb.2024.1324099.
[115] A.R. Khan, B. Ahmad, M. Khan, M.A. Khan, S. Sultan, K. Sultana, et al., Production of single cell protein (SCP) from the peel waste of pea, potato, and banana by *Aspergillus flavus* NRRL 21882 as an efficient organic poultry supplement, ACS Omega 9 (2024) 37763–37770, https://doi.org/10.1021/acsomega.4c03317.
[116] A. Koga, S. Takiguchi, Y. Tani, K.-I. Ozaki, T. Maki, H. Okuhata, et al., Comparison of the probiotic effects of freshwater and marine photosynthetic bacteria in kuruma shrimp (*Marsupenaeus japonicus*) culture, J. Appl. Aquac. (2022) 1–17, https://doi.org/10.1080/10454438.2022.2044958.
[117] L. Peng, W. Lou, Y. Xu, S. Yu, C. Liang, A. Alloul, et al., Regulating light, oxygen and volatile fatty acids to boost the productivity of purple bacteria biomass, protein and co-enzyme Q10, Sci. Total Environ. 822 (2022) 153489, https://doi.org/10.1016/j.scitotenv.2022.153489.
[118] X. Li, J. Huang, Z. Shi, Y. Xie, Z. Xu, J. Long, G. Song, Y. Wang, G. Zhang, X. Luo, Reduction and adsorption of uranium (VI) from aqueous solutions using nanoscale zero-valent manganese, J. Environ. Manag. 342 (2023) 118088.
[119] M. Li, Energy recovery applications of microbial fuel cells in wastewater treatment, J. Energy Biosci. 15 (2024).
[120] S. Malik, S. Kishore, A. Dhasmana, P. Kumari, T. Mitra, V. Chaudhary, R. Kumari, J. Bora, A. Ranjan, T. Minkina, A perspective review on microbial fuel cells in treatment and product recovery from wastewater, Water 15 (2) (2023) 316.
[121] P. Karka, I. Johannsen, S. Papadokonstantakis, Hydrothermal liquefaction integrated with wastewater treatment plants: life cycle assessment and techno-economic analysis of process system options, Sustain. Energy Fuels 8 (15) (2024) 3438–3451.
[122] A. Yadav, E.R. Rene, M. Sharma, I. Jatain, M.K. Mandal, K.K. Dubey, Valorization of wastewater to recover value-added products: a comprehensive insight and perspective on different technologies, Environ. Res. 214 (2022) 113957.
[123] A. Morillas-España, T. Lafarga, A. Sánchez-Zurano, F.G. Acién-Fernández, C. González-López, Microalgae-based wastewater treatment coupled to the production of high-value agricultural products: current needs and challenges, Chemosphere 291 (2022) 132968.
[124] B. Śniatała, H.E. Al-Hazmi, D. Sobotka, J. Zhai, J. Mąkinia, Advancing sustainable wastewater management: a comprehensive review of nutrient recovery products and their applications, Sci. Total Environ. 937 (2024) 173446.

[125] R. Shen, Y. Jiang, Z. Ge, J. Lu, Y. Zhang, Z. Liu, Z.J. Ren, Microbial electrolysis treatment of post-hydrothermal liquefaction wastewater with hydrogen generation, Appl. Energy 212 (2018) 509–515.
[126] M.K. Hassan, S. Senko, A. Villa, E. Grafova, A. Pappinen, S. Kuittinen, Techno-economic evaluation of biofertilizer production using wastewater biosolids: case study from municipal wastewater treatment plants in northwest region of Russia, J. Mater. Cycles Waste Manag. 25 (2023) 3380–3394, https://doi.org/10.1007/s10163-023-01766-w.
[127] M. Bagheri, M. Öhman, E. Wetterlund, Techno-economic analysis of scenarios on energy and phosphorus recovery from mono- and co-combustion of municipal sewage sludge, Sustainability 14 (2022) 2603, https://doi.org/10.3390/su14052603.
[128] Á. Mayor, S. Vinardell, K. Ganesan, C. Bacardí, J.L. Cortina, C. Valderrama, Life-cycle assessment and techno-economic evaluation of the value chain in nutrient recovery from wastewater treatment plants for agricultural application, Sci. Total Environ. 892 (2023) 164452, https://doi.org/10.1016/j.scitotenv.2023.164452.
[129] H. Wu, E.M. Hernández, C. Vaneeckhaute, Techno-economic analysis of nutrient recovery from urine: centralized treatment of hydrolyzed urine vs. decentralized treatment of fresh urine, Sci. Total Environ. 956 (2024) 177295, https://doi.org/10.1016/j.scitotenv.2024.177295.
[130] A. Lugo, X. Xu, I.S.A. Abeysiriwardana-Arachchige, G.L.C.L. Bandara, N. Nirmalakhandan, P. Xu, Techno-economic assessment of a novel algal-membrane system versus conventional wastewater treatment and advanced potable reuse processes: Part II, J. Environ. Manag. 331 (2023) 117189, https://doi.org/10.1016/j.jenvman.2022.117189.
[131] S. Khune, B. Otieno, J. Kabuba, G. Ochieng, P. Osifo, Techno-economic assessment of codigestion of waste activated sludge with food waste for enhanced bioresource recovery, BioEnergy Res. 18 (2025) 36, https://doi.org/10.1007/s12155-025-10836-w.
[132] R.R. Bora, R.E. Richardson, F. You, Resource recovery and waste-to-energy from wastewater sludge via thermochemical conversion technologies in support of circular economy: a comprehensive review, BMC Chem. Eng. 2 (2020) 8, https://doi.org/10.1186/s42480-020-00031-3.
[133] J. Sitarz, M. Pahle, S. Osorio, G. Luderer, R. Pietzcker, EU carbon prices signal high policy credibility and farsighted actors, Nat. Energy 9 (2024) 691–702, https://doi.org/10.1038/s41560-024-01505-x.
[134] J.S. Sravan, L. Matsakas, O. Sarkar, Advances in biological wastewater treatment processes: focus on low-carbon energy and resource recovery in biorefinery context, Bioengineering 11 (3) (2024) 281.
[135] J. Marcal, T. Bishop, J. Hofman, J. Shen, From pollutant removal to resource recovery: a bibliometric analysis of municipal wastewater research in Europe, Chemosphere 284 (2021) 131267.
[136] D. Renfrew, V. Vasilaki, E. Nika, G.A. Tsalidis, E. Marin, E. Katsou, Systematic assessment of wastewater resource circularity and sustainable value creation, Water Res. 251 (2024) 121141.
[137] F. Zhu, E.K. Cakmak, Z. Cetecioglu, Phosphorus recovery for circular economy: application potential of feasible resources and engineering processes in Europe, Chem. Eng. J. 454 (2023) 140153, https://doi.org/10.1016/j.cej.2022.140153.
[138] L. Egle, H. Rechberger, J. Krampe, M. Zessner, Phosphorus recovery from municipal wastewater: an integrated comparative technological, environmental and economic assessment of P recovery technologies, Sci. Total Environ. 571 (2016) 522–542.
[139] Ç. Akyol, A. Foglia, E.G. Ozbayram, N. Frison, E. Katsou, A.L. Eusebi, F. Fatone, Validated innovative approaches for energy-efficient resource recovery and re-use from municipal wastewater: from anaerobic treatment systems to a biorefinery concept, Crit. Rev. Environ. Sci. Technol. 50 (9) (2020) 869–902.
[140] C. Linvill, M. Butkus, E. Bennett, M. Wait, A. Pytlar, A. Pfluger, Energy balances for proposed complete full-scale anaerobic wastewater treatment facilities, Environ. Eng. Sci. 40 (11) (2023) 482–493, https://doi.org/10.1089/ees.2023.0076.
[141] R. Dalke, D. Demro, Y. Khalid, H. Wu, M. Urgun-Demirtas, Current status of anaerobic digestion of food waste in the United States, Renew. Sustain. Energy Rev. 151 (2021) 111554.
[142] A. Pfluger, J. Coontz, V. Zhiteneva, T. Gulliver, L. Cherry, L. Cavanaugh, L. Figueroa, Anaerobic digestion and biogas beneficial use at municipal wastewater treatment facilities in Colorado: a case study examining barriers to widespread implementation, J. Clean. Prod. 206 (2019) 97–107.
[143] R. Garrido, L.F. Cabeza, V. Falguera, An overview of bioplastic research on its relation to national policies, Sustainability 13 (14) (2021) 7848.
[144] K.U. Shah, I. Gangadeen, Integrating bioplastics into the US plastics supply chain: towards a policy research agenda for the bioplastic transition, Front. Environ. Sci. 11 (2023) 1245846.
[145] A.A. Werkneh, Decentralized constructed wetlands for domestic wastewater treatment in developing countries: field-scale case studies, overall performance and removal mechanisms, J. Water Process Eng. 57 (2024) 104710, https://doi.org/10.1016/j.jwpe.2023.104710.
[146] R. Vaidya, K. Verma, M. Kumar, C. Hoysall, L. Rao, Assessing wastewater management challenges in developing countries: a case study of India, current status and future scope, Environ. Dev. Sustain. 26 (2023) 19369–19396, https://doi.org/10.1007/s10668-023-03540-2.
[147] M. Qadir, P. Drechsel, B. Jiménez Cisneros, Y. Kim, A. Pramanik, P. Mehta, O. Olaniyan. Global and regional potential of wastewater as a water, nutrient and energy source, Natural resources forum, Blackwell Publishing Ltd., Oxford, UK, 2020, pp. 40–51, 1.
[148] J.K. Debrah, G.K. Teye, M.A. Dinis, Barriers and challenges to waste management hindering the circular economy in Sub-Saharan Africa, Urban Sci. 6 (3) (2022) 57.
[149] S. De, M. Coutard, J. Hoinkis, Solar powered membrane bioreactor (MBR) treating wastewater for reuse at a hospital in Kampala, Uganda: results of pilot-scale trials, Environ. Chall. 16 (2024) 100986, https://doi.org/10.1016/j.envc.2024.100986.
[150] Y.D. Tan, J.S. Lim, Feasibility of palm oil mill effluent elimination towards sustainable Malaysian palm oil industry, Renew. Sustain. Energy Rev. 111 (2019) 507–522.
[151] F.F. Freitas, U.R. Coelho, S.T. Silva, A.A. Gomes, R.M. Barros, G.L. Filho, E. E. Lora, I.F. dos Santos, Study of the potential for energy use of biogas from a wastewater treatment plant to a medium-sized city: a technical, economic and environmental analysis, Waste Biomass Valorization 13 (8) (2022) 3509–3521.
[152] D.J. Hernandez, A.S. David, E.S. Menges, C.A. Searcy, M.E. Afkhami, Environmental stress destabilizes microbial networks, ISME J. 15 (6) (2021) 1722–1734.
[153] L.S. Lopes, A.P. Rosa, J.S. Marco, G.R. Possetti, T.C. Mesquita, Energy potential of biogas and sludge from UASB reactors in the state of Paraná, Brazil, Revista Ambiente & Água 15 (1) (2020) e2398.
[154] E. Eghombi, H. Kim, Y.H. Choi, M.H. Baek, M.N. Nadagouda, P.K. Park, S. Chae, Efficient phosphorus recovery from municipal wastewater using enhanced biological phosphorus removal in an anaerobic/anoxic/aerobic membrane bioreactor and magnesium-based pellets, Membranes 12 (2) (2022) 210.
[155] Y.R. Loh, D. Sujan, M.E. Rahman, C.A. Das, Sugarcane bagasse—The future composite material: a literature review, Resour. Conserv. Recycl. 75 (2013) 14–22.
[156] A. Ghorpade, M.M. Ahammed, Water treatment sludge for removal of heavy metals from electroplating wastewater, Environ. Eng. Res. 23 (1) (2018) 92–98.
[157] T. Alvarino, S. Suarez, J. Lema, F. Omil, Understanding the sorption and biotransformation of organic micropollutants in innovative biological wastewater treatment technologies, Sci. Total Environ. 615 (2018) 297–306.
[158] M. Zielińska, A. Ojo, Anaerobic membrane bioreactors (ANMBRs) for wastewater treatment: recovery of nutrients and energy, and management of fouling, Energies 16 (6) (2023) 2829.
[159] O.Z. Wada, T.D. Afolalu, C.J. Maihankali, A.S. Olojo, D.B. Olawade, Dependence of rural communities on unsafe water sources: case study of Tinda Village, Northeastern Nigeria, Int. J. Environ. Clim. Change (2021) 76–87, https://doi.org/10.9734/ijecc/2021/v11i230364.
[160] O.Z. Wada, D.B. Olawade, E.O. Oladeji, A.O. Amusa, E.O. Oloruntoba, 'School water, sanitation, and hygiene inequalities: a bane of sustainable development goal six in Nigeria, Can. J. Public Health 113 (2022) 622–635, https://doi.org/10.17269/s41997-022-00633-9.
[161] World Bank Group (2017) Reducing inequalities in water supply, sanitation, and hygiene in the era of the Sustainable Development Goals: synthesis report of the WASH Poverty Diagnostic Initiative. Washington DC. Available at: 〈https://openknowledge.worldbank.org/handle/10986/27831〉.
[162] S. Wainaina, M.K. Awasthi, I.S. Horvath, M.J. Taherzadeh, Anaerobic digestion of food waste to volatile fatty acids and hydrogen at high organic loading rates in immersed membrane bioreactors, Renew. Energy 152 (2020) 1140–1148.
[163] V. Díaz, J.C. Leyva-Díaz, M.C. Almécija, J.M. Poyatos, M. del Mar Muñío, J. Martín-Pascual, Microalgae bioreactor for nutrient removal and resource recovery from wastewater in the paradigm of circular economy, Bioresour. Technol. 363 (2022) 127968.
[164] F.M. Santos, J.C. Pires, Nutrient recovery from wastewaters by microalgae and its potential application as bio-char, Bioresour. Technol. 267 (2018) 725–731.