Water Reuse

IWA PUBLISHING

Water Reuse Vol 00 No 0, 1 doi: 10.2166/wrd.2022.038

Adopting the circular model: opportunities and challenges of transforming wastewater treatment plants into resource recovery facilities in Saudi Arabia

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ABSTRACT

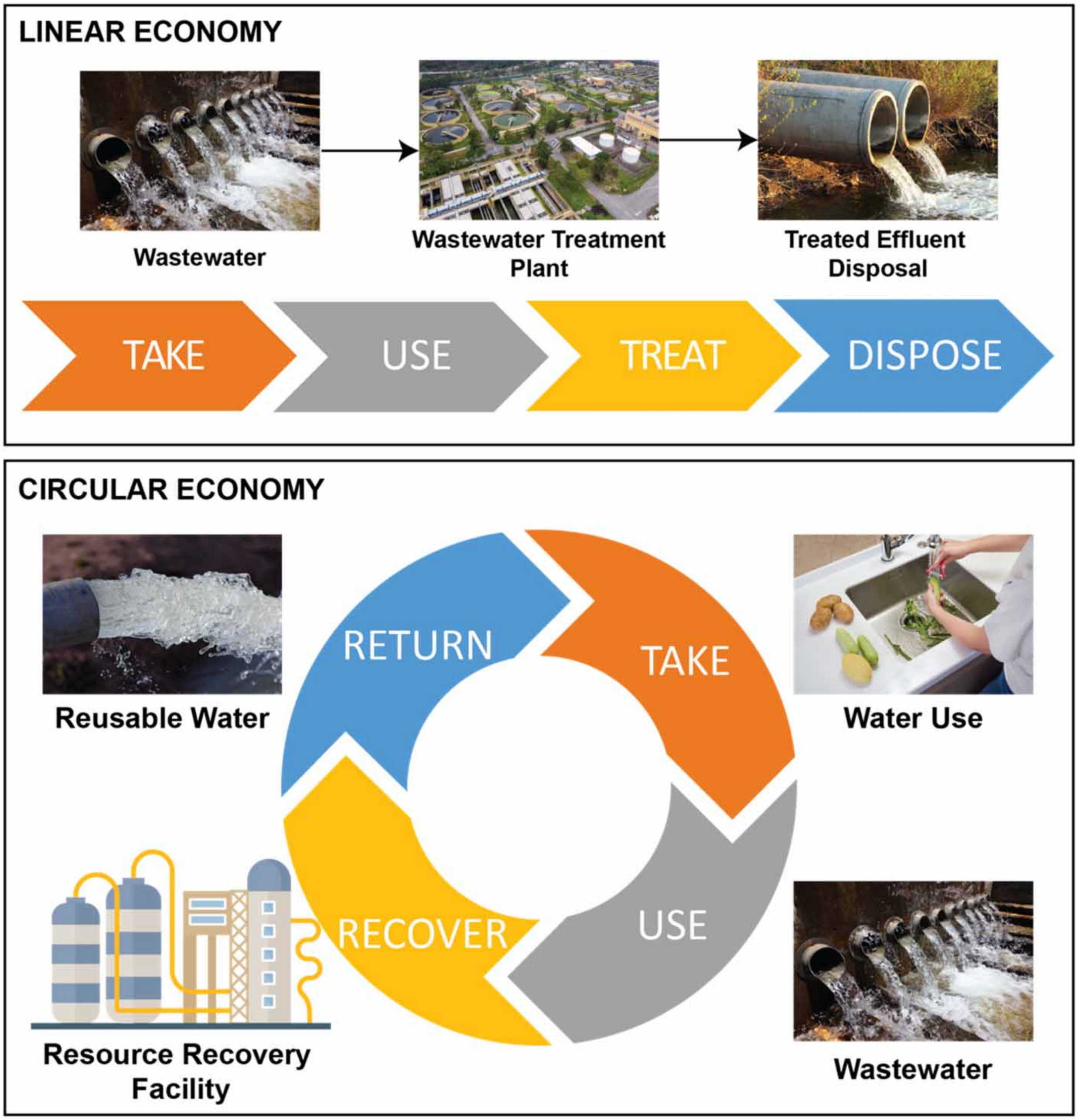
With the ever-growing population, water, energy, and resources need to be used carefully, reused, and renewed. There is an increasing global interest in resource recovery from 'waste', which is driven by sustainability and environmental concerns and motivated by the potential for economic benefits. A new era in waste (water) management is being realized where wastewater treatment is becoming part of the circular economy by integrating the production of reusable water with energy and resource recovery. In this new perspective, wastewater is no longer seen as a waste to be treated with energy expenditure but rather as a valuable resource of freshwater, energy, nutrients (nitrogen and phosphorous), and materials (e.g., bioplastics, cellulose fibres, and alginate). In this review paper, the conversion of wastewater treatment plants (WWTPs) into resource recovery factories (RRFs) is presented as one of the ways forward to achieve a circular economy in the water sector for the Kingdom of Saudi Arabia (KSA). The advanced technologies, some highlighted in the article, can be installed, integrated, or retrofitted into existing WWTPs to create RRFs enabling the recovery of freshwater, cellulose, alginate-like exopolymers (bio-ALE), and biogas from municipal wastewater achieving climate neutrality, decarbonization, and production of new and promising resources. The article highlights the need for modular, adaptive, and/or decentralized approaches using sustainable technologies such as aerobic granular sludge (AGS)-gravity-driven membrane (AGS-GDM), anaerobic electrochemical membrane bioreactor (AnEMBR), and anaerobic membrane bioreactor (AnMBR) for conducive localized water reuse. The increase in reuse will reduce the pressure on non-renewable water resources and decrease dependency on the energy-intensive desalination process. This article also outlines the water challenges that are arising in KSA and what are the major water research programmes/themes undertaken to address these major challenges.

Key words: circular economy, resource recovery, waste to resource, water reuse

HIGHLIGHTS

- The conversion of WWTPs into RRFs for the circular economy in Saudi Arabia.
- RRFs enable the recovery of freshwater and resources from municipal wastewater.
- Modular, adaptive, decentralized technologies to promote water reuse.
- Water reuse reduces the pressure on non-renewable water resources and dependency on desalination.
- Seawater toilet flushing to reduce demand for desalination

GRAPHICAL ABSTRACT



1. FRESHWATER SUPPLY AND DEMAND

The grand challenges facing society in the current century are water, energy, food security, and climate change (UNDP 2022). These challenges are exacerbated due to the rapidly growing human population, leading to increased resource (water, energy, food, and chemicals) consumption with a concomitant production of large volumes of 'used resources', commonly recognized as waste. Water is the most widely used (100-fold greater) natural resource compared to all other natural resources combined (Rittmann & McCarty 2020). It is required to satisfy the domestic, agricultural, and industrial needs of around 8 billion people on the planet. However, readily available freshwater with adequate quality represents less than 1% of the total water on Earth (Gleick 1993). The ever-growing population, urbanization and economic development are putting unprecedented pressure on finite water resources, especially in arid regions. Around 2 billion people are living in countries or regions with 'absolute' water scarcity (<500 m^3/year/capita), and two-thirds of the world population could be under 'stress' conditions (between 500 and 1,000 m^3/year/capita) (FAO 2022b). The environmental services and water-related engineered infrastructure cannot handle the wastewaters of all water users and the discharge of untreated wastewaters generated by human activities contaminates freshwater natural resources.

The situation is even worse in the Gulf region, including Bahrain, Kuwait, Oman, Qatar, the Kingdom of Saudi Arabia (KSA), and the United Arab Emirates (UAE). This region is characterized by scarce rainfall (<100 mm/year), high evaporation rates (>3 K mm/year), and scarcity of renewable water resources (Mohammad ElNesr & Abu-Zreig 2010; Aleisa & Al-Zubari 2017). The average annual per capita renewable water sources have already reached the chronic water scarcity line (<500 m^3/capita/year, Table 1), which would adversely impact socio-economic development (FAO 2022b). The region relies mainly on energy-intensive seawater and brackish water desalination, followed by extraction from non-renewable groundwater resources, to satisfy their demand for water.

KSA receives scarce rainfall (59 mm/year), high evaporation rates (>3 K mm/year (Mohammad ElNesr & Abu-Zreig 2010)) and has limited (2.4 billion m^3/year) renewable water resources (Figure 1, https://data.gov.sa/). There is a high reliance on non-renewable groundwater sources (constituting around 35% of KSA's water supply in 2018) and desalinated water accounts for about 59% (SWPC 2020). The total water withdrawal is, however, around 23.8 billion m^3/year, out of which 82% is consumed by the agricultural sector, and 18% by the combined domestic and industrial sectors (SWPC 2019; FAO 2022b). Most of the agriculture sector is reliant on non-renewable groundwater, which is rapidly depleting (Famiglietti 2014). The current national municipal water demand is about 3.4 billion m^3/year out of which about 2 billion m^3/year is supplied through desalination plants (Figure 1, https://data.gov.sa/). The extensive use of non-renewable groundwater sources has contributed to KSA's high water stress level (Figure 1), calculated as a ratio of freshwater withdrawal as a proportion of available renewable freshwater resources. The country's groundwater has been almost depleted in little more than a generation (Griffin *et al.* 2021). The Ministry of Environment, Water and Agriculture (MEWA), has recently set a directive of reaching an urban water supply mix of 90% desalinated water and 10% non-renewable groundwater by 2030 (SWPC 2020).

KSA, the largest producer of desalinated water, has experienced rapid economic and population growth and development over the past nine decades since oil was discovered. In 1970, KSA had a population of 5.8 million; it increased to 35 million in 2020 and is expected to increase to 40.1 million by 2030 (GAS 2020). Desalination plants will continue to be developed to cater for the growing urban water demand as well as shortages resulting from reduced reliance on ground and surface water. In 2026, the existing and committed desalinated water supply is expected to provide 2.18 billion m^3/year (SWPC 2020). On

Table 1 | Availability of water resources in GCC countries

		Country					
Description		**Bahrain**	**Kuwait**	**Oman**	**Qatar**	**KSA**	**UAE**
Population [million]	2022	1.8	4.4	5.5	3.0	36.6	10.1
	2030	2.1	4.8	6.3	3.4	40.9	10.8
Area	[km^2]	778	17,820	309,500	11,610	2,149,690	83,600
Total renewable water resources (TRWR)	[km^3/year]	0.116	0.020	1.400	0.058	2.4	0.15
TRWR per capita	[m^3/inhab/year]	65	5	256	19	71	15
Total water withdrawal	[km^3/year]	0.434	1.250	1.873	0.881	23.8	5.1
Water withdrawal per capita	[m^3/inhab/year]	244	285	342	296	656	500
Water withdrawal as % of TRWR	%	374	6,250	134	1,519	1,000	3,370
Desalinated water produced	[km^3/year]	0.242	0.420	0.330	0.634	2.18	2.011
Produced municipal wastewater	[km^3/year]	0.151	0.292	0.108	0.274	2.7	0.751
Treated municipal wastewater	[km^3/year]	0.090	0.216	0.028	0.274	1.7	0.7
Reuse of treated municipal wastewater	[km^3/year]	0.0	0.1	0.1	0.1	0.5	0.5

Source: SWPC 2020; FAO 2022a; KSA 2022.

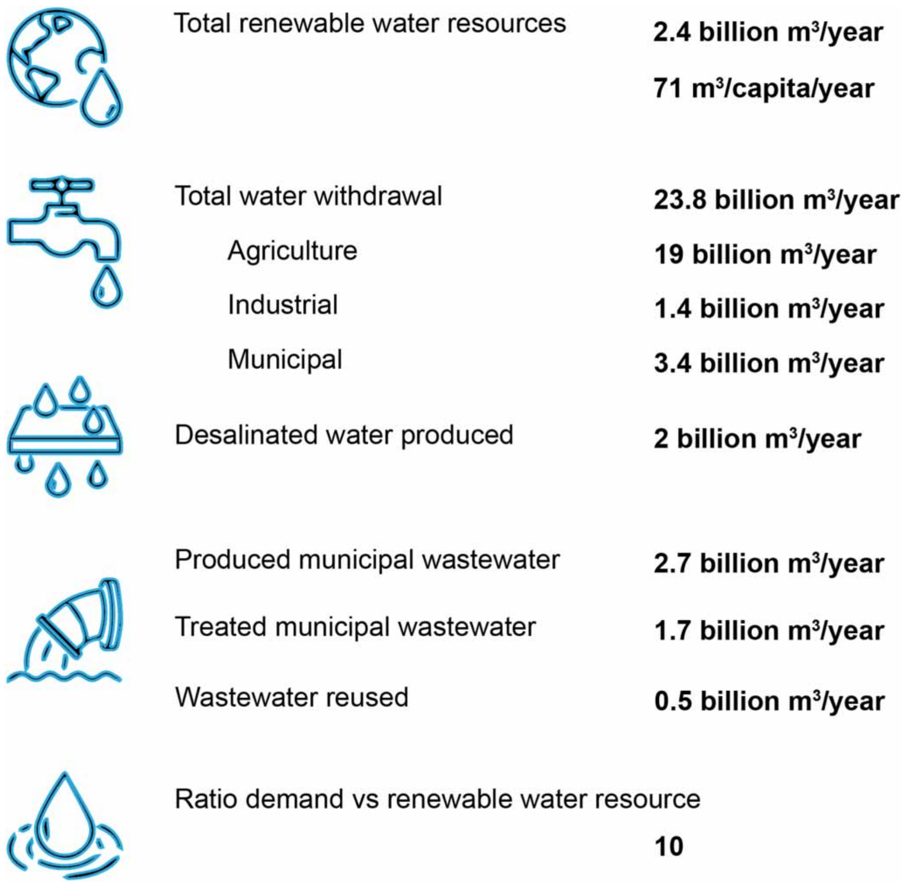


Figure 1 | The current situation of water availability and demand in KSA. The ratio between water demand and renewable water resources is calculated as the ratio of freshwater withdrawal as a proportion of available renewable freshwater resources (*Source*: FAO 2022a; KSA 2022; SWPC 2020).

the demand side, KSA is among the world's top five consumers of water on a per capita basis currently standing at 360 L/day, which is significantly higher than other developed countries (SWPC 2020). Total water demand is expected to increase to 14.5 million m^3/day by 2026 with a gap of 4.5 million m^3/day estimated in 2026 at the national level. Out of this national water gap, a 4.1 million m^3/day gap is expected to be served through newly constructed or planned seawater reverse osmosis (SWRO) mainly due to its economic advantages (IDA 2020). SWRO requires 3–8 kWh/m^3 of desalinated water for large-to-medium-size plants, respectively (Al-Karaghouli & Kazmerski 2013). For small-size plants, it can be as high as 15 kWh/m^3 (Al-Karaghouli & Kazmerski 2013). Assuming an average energy consumption of 6 kWh/m^3, more than 15 billion kWh energy is used by desalination plants in KSA. Currently, KSA desalination plants emit on average 2.5 kg CO_2/m^3 of desalinated water produced (Reddy & Ghaffour 2007), which corresponds to 5 million tonnes of CO_2/year through desalination plants (producing about 2 billion m^3 water/year) only.

Given the stress on water resources in this region and the number of energy resources allocated to desalination and their carbon footprint, it is imperative to maximize water-use efficiency. In fact, there is an emerging interest worldwide for resource recovery from waste streams towards a circular economy. In this regard, wastewater (i.e., used water) is no longer viewed as a waste material to treat with energy expenditure, but rather as a valuable resource of water, energy, nutrients (nitrogen and phosphorous), and materials (e.g., bioplastics, cellulose fibres, alginate, and metals). Most importantly, the reuse of treated water is becoming mandatory to fully address the water scarcity issue in KSA and many water-scarce countries around the world. Transforming wastewater treatment plants (WWTPs) into resource recovery facilities (RRFs) is currently a key driver for research and development of next-generation wastewater treatment technologies. This article outlines the water challenges that are arising in KSA and what are the major water research programmes/themes undertaken to address these major challenges.

2. WHY SHOULD KSA EMBRACE A CIRCULAR ECONOMY MODEL IN THE WATER SECTOR?

In the standard linear economy model, raw materials are extracted, processed, and turned into products which are then discarded at the end of their life (Figure 2). For example, in the current municipal cycle, wastewater is treated via energy-intensive processes and the treated sewage effluent is discharged back into the sea. In contrast, the circular economy model maximizes the sustainable use and value of resources, eliminating waste and benefiting both the economy and the environment (Kirchherr *et al.* 2017). In this model, goods and services are produced to minimize waste generation, greenhouse gas (GHG) emissions, energy consumption, and material consumption. Most of the freshwater in KSA is currently produced via desalination processes, which is energy intensive; moreover, the Gulf's waters are already 25% saltier than the global average which increases desalination costs (MEWA 2017). Brine from desalination plants (>10% salinity) is discharged back into the sea, which is detrimental to the marine ecosystem. As regulations on brine discharge become stringent

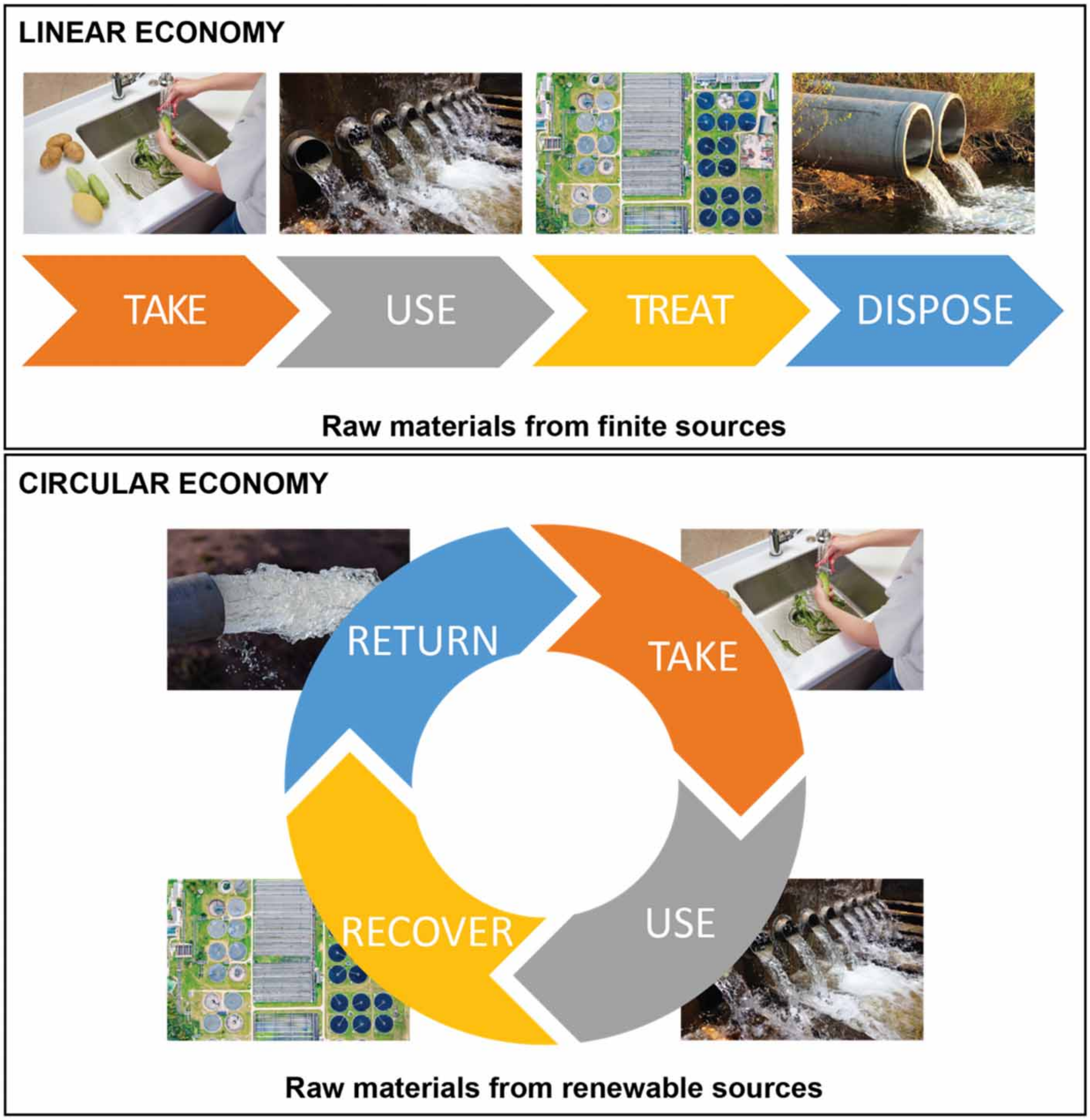


Figure 2 | Going circular—the difference between a traditional linear and a circular economy model.

and subsidies on fossil-fuel-based energy wane, future desalination cost is likely to increase. Therefore, energy-efficient desalination technologies with brine management/mining and energy-efficient wastewater treatment technologies are needed to achieve circularity and sustainability in the water sector in KSA.

Wastewater remains a largely untapped resource for the circular economy. For example, valuable substances in wastewater include water, phosphorus, and ammonium that can be used as recovered fertilizer, lipids as biofuel, and cellulose for biochemicals and bio-composites. In addition, wastewater provides a source to produce biodegradable bioplastics (i.e., polyhydroxyalkanoates (PHA)), a possible replacement for the petroleum-based plastics that biodegrade very slowly and affect marine life. As a result, these carbon-based elements are no longer directly converted to CO_2 and/or CH_4 as is happening in the current practice of wastewater treatment but are converted to valuable products leading to a decrease in GHG emissions. Smarter use of secondary raw materials will create a safe and sustainable supply of raw materials to the industry. Smarter use of resources from wastewater will also help protect the environment and at the same time preserve essential resources for current and future generations.

The circular economy model also reduces threats to future growth that come from unsustainable patterns of resource use. It takes account of the depletion and waste of natural resources as a loss to the economy, which is not captured in existing GDP measures. According to a study, a circular economy model could generate up to US$138 billion (SAR 518 billion) in economic benefits for the Gulf Cooperation Council (GCC) between 2020 and 2030 (Bejjani *et al.* 2018). These benefits would largely arise from enhanced competitiveness, a lowering of environmental pressures and costs, making raw material supply chains more secure, boosting industry innovation, and generating new jobs.

3. ENERGY-EFFICIENT WATER DESALINATION AND BRINE MANAGEMENT

Desalination is the lifeline of KSA, and it provides a significant amount of fresh water to meet national water demand. There is always a desire to develop innovative desalination technologies which require less energy input and contribute less to global warming. There is rapid growth in KSA desalination capacity, and six new installations based on the reverse osmosis (RO) process will further add 3 M m^3/day capacity (Narayanan 2022). The desalination demand can be reduced by using impaired quality water sources, such as seawater, for toilet flushing and treated wastewater for non-potable reuse (discussed in Sections 4 and 6). The main challenge associated with desalination is better management of brine discharge, which is especially critical when desalinating saline groundwater in inland areas. However, RO is still facing challenges, such as limited water recovery and biofouling, especially in areas where feed water has higher salinity and nutrient concentrations such as the Gulf water, further increasing the already intensive energy requirements. An assessment of the concentrations and fate of trace elements during saline water treatment will enable to evaluate the potential for the development of directed strategies for brine mining combined with zero liquid discharge (ZLD). The current research programme on desalination aims to enhance the total water recovery and reduce energy and chemical consumption by:

- Optimizing the RO process through the development of performance control and prediction tools for efficient membrane cleaning and an accurate estimation of the osmotic pressure throughout the pressure vessel to minimize the energy input and reduce (bio)fouling (Desmond *et al.* 2022).
- Integrating RO with solar energy (BELLINI 2022).
- Treating the RO brine using novel direct contact evaporation and condensation (DCSEC) integrated with membrane distillation (MD) processes (Chen *et al.* 2021). Both DCSEC and MD operate at moderate temperatures (~50–70 °C) which makes them suitable for the use of solar energy. The whole hybrid process is targeting close to ZLD. Both RO and the proposed novel DCSEC-MD processes will play an important role in future desalination installations due to their flexible scalability from very small-to-extra-large capacities, which will have a direct socio-economic impact on KSA.

4. SEAWATER TOILET FLUSHING TO REDUCE DEMAND FOR DESALINATION

Demand for seawater desalination could be reduced if seawater is used for toilet flushing. Over 50% of the world's population resides within 60 km of the coast, and seawater can be directly utilized for non-potable uses such as toilet flushing (~30% of the total domestic water demand) to reduce the demand on freshwater resources and desalination – an energy-intensive process. The use of seawater for toilet flushing is already in practice in several coastal cities (e.g., Hong Kong), and it is anticipated that more coastal cities may implement seawater for toilet flushing. The saline wastewater generated from seawater toilet flushing practices could produce hyperosmotic stress on the microbiome of WWTPs (Figure 3). Also, the

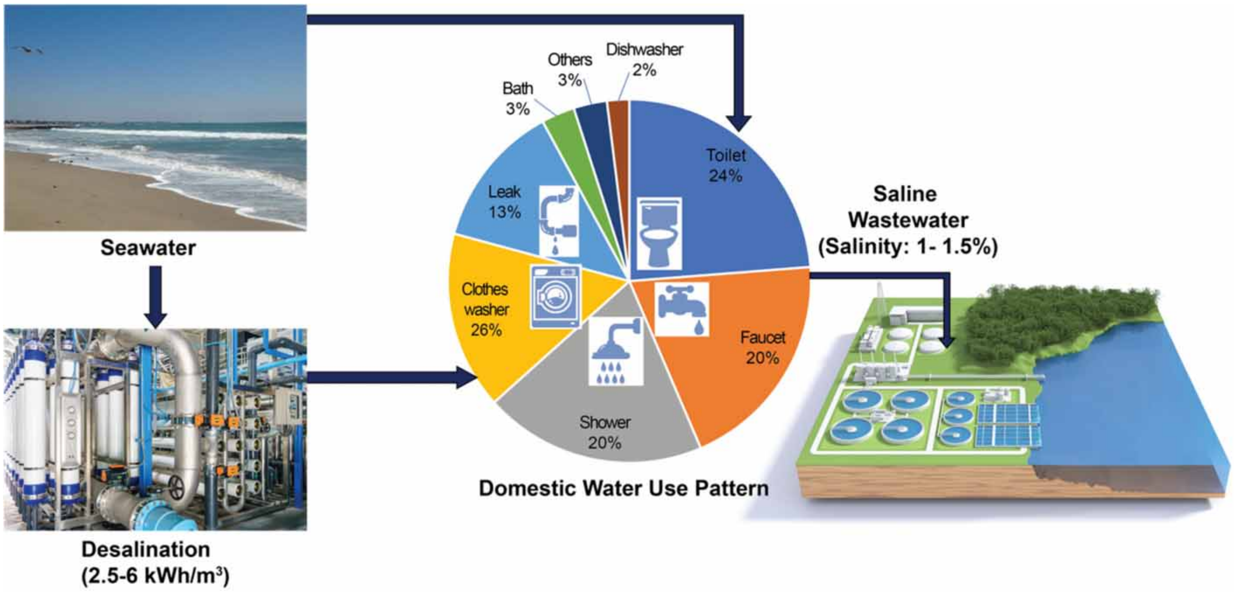


Figure 3 | The seawater toilet flushing produces saline wastewater with a salinity of 1–1.5%.

discharge of untreated or partially treated saline wastewater could degrade the water quality of receiving water bodies. Thus, receiving water bodies cannot be directly used for producing potable drinking water (via desalination) (Panagopoulos 2022a, 2022b; Panagopoulos & Giannika 2022). Therefore, there is a need to develop more robust wastewater treatment technologies for the treatment of saline wastewaters before discharging the treated effluent to the sea or reusing it to irrigate salt-tolerant crops (AL-KHUDAIR 2019).

The aerobic granular sludge (AGS) process has been shown to be a robust technology for the treatment of saline wastewaters having a salinity of 1% (Wang *et al.* 2017, 2018). Similarly, marine anaerobic ammonium oxidation (anammox) bacteria, which have intrinsic tolerance to salinity compared to freshwater anammox bacteria, enriched in a membrane bioreactor (MBR) showed good removal of ammonium (NRR of 0.27 ± 0.01 kg-N/m^3/day and ~92% N-removal efficiency) from saline wastewater with a salinity of 1.2% (Ali *et al.* 2020a, 2019a, 2020b). These findings have significant implications for applying AGS or marine anammox process for treating saline wastewater generated from toilet flushing practices. It is anticipated that more cities will adopt seawater toilet flushing practices to relieve the stress of the ever-increasing demand for freshwater (Yang *et al.* 2015). Furthermore, the problems associated with the corrosion of pipelines and equipment induced by seawater toilet flushing practices can now be solved or mitigated satisfactorily with the experience gained from previous practices (Tang *et al.* 2007).

5. SUPERHYDROPHOBIC SAND FOR GROWING MORE FOOD WITH LESS WATER

KSA landmass experiences arid and semi-arid climates, characterized by high temperature, intense solar radiation, and extremely low annual precipitation; these conditions, coupled with the lack of surface water resources (e.g., rivers, lakes, and ponds) and nutrient-deficient sandy soils with low water-holding ability, pose significant challenges for growing plants/trees (Sultana & Nasrollahi 2018; Sahour *et al.* 2020). While plastic sheets have been used to reduce water evaporation from the topsoil in arid climates, their eventual disposal in landfills limits their sustainability (Kasirajan & Ngouajio 2012). In response, Mishra & co-workers have pioneered Superhydrophobic sand (SHS), a mulching approach that combines common sand or sandy soils with a nanoscale coating of paraffin wax (Gallo *et al.* 2022). When applied as a 5–10 mm layer on the topsoil, SHS acts as a dry diffusive barrier and dramatically curtails evaporative water loss (Figure 4). As a result, the moisture content is significantly higher in the mulched soil that plants utilize for transpiration, nutrients uptake, and so on; consequently, plant health and yield are significantly higher as evidenced from multiyear field trials (Gallo *et al.* 2022) and controlled environment studies on a variety of crops (Odokonyero *et al.* 2022). Ongoing experiments in this translational research programme include quantifying the effects of SHS mulching when irrigation is facilitated via treated wastewater

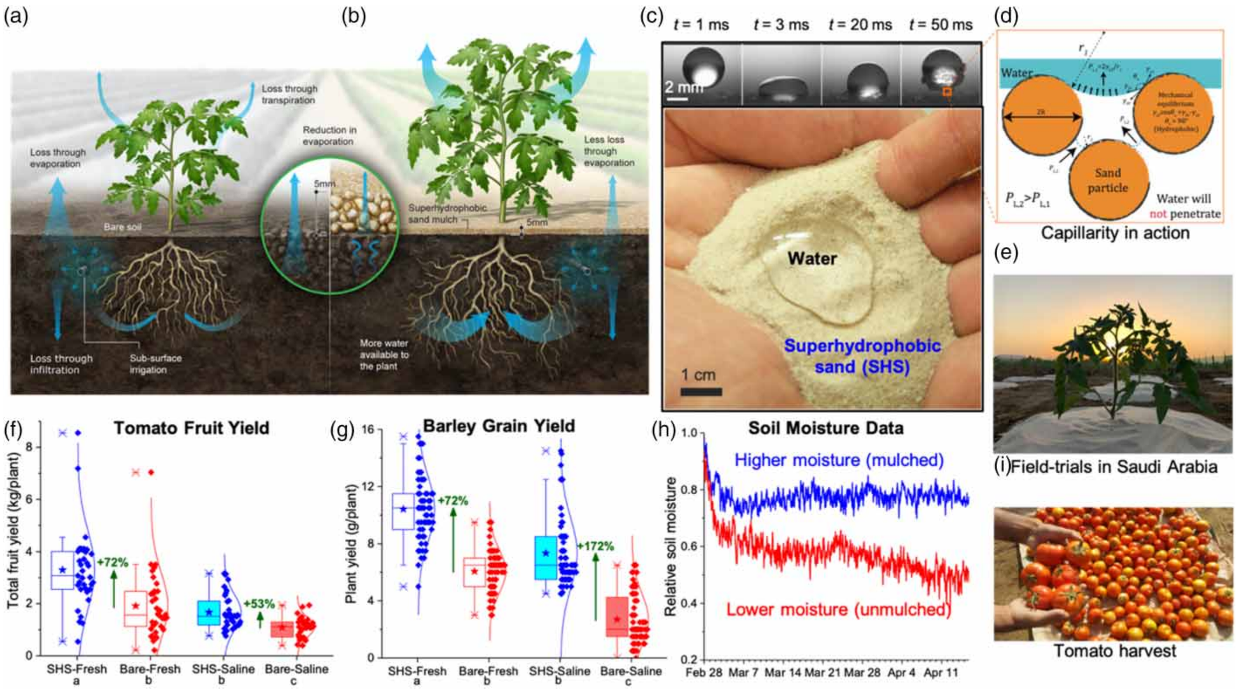


Figure 4 | Superhydrophobic sand (SHS). (a–b) Concept illustration: SHS mulch prevents evaporative loss of water from the topsoil and enhances plant health and yield. (c) The water repellence of SHS is underscored by water droplets rebounding from a packed SHS bed (top) and water's inability to infiltrate it (bottom). (d) Water repellence of SHS stems from capillary forces. (e) Field application of SHS on tomato (*Solanum lycopersicum*) plants in KSA. (f–g) Representative results demonstrating enhancement in tomato fruit production and barley (*Hordeum vulgare*) grain yield in field experiments in KSA. (h) Representative soil moisture data in a field experiment underscores SHS' ability to reduce water evaporation from the topsoil. (i) Representative image of tomato harvest—more food with limited freshwater (*Note*: this figure has been adapted from Gallo *et al.* (2022) under the Creative Commons 4.0 licence from the American Chemical Society).

effluent from an anaerobic process; time-dependent loss of SHS wax layer and water repellence due to microbial activity in the soil; and scaling up SHS manufacturing.

6. RESOURCE RECOVERY FACILITY

Regarding the recovery of resources from sewage, there are different options, paths, and priorities. The current focus is on biogas, cellulose, bioplastics, phosphate, and alginate-like exopolymers (also known as bio-ALE). There are currently 91 medium-to large-scale centralized WWTPs in KSA treating 1.7 billion m^3/year of wastewater (Table 2). The creation of new RRF is capital intensive compared to upgrading existing WWTPs to RRFs; and some of the WWTPs in KSA are quite big, especially in big cities such as Riyadh, Jeddah, and Mecca. Economies of scale can play an important role in the cost of recovered resources. This implies that RRFs will probably be created in big cities first that are served with large-scale centralized WWTPs. When experience has been gained and the costs of installations have dropped, it is expected that RRFs will also be built in smaller cities.

The different resource recovery technologies are in different stages of development. Normally the stages of pre-development, development, take-off, acceleration, and stabilization are discerned (Figure 5). In the RRF, some resources are in the take-off stage such as cellulose and bio-ALE, and phosphate is in an acceleration stage. Biogas from anaerobic digestion (AD) is in the stabilization stage, whereas bioplastics are in the early stages of development (van Leeuwen *et al.* 2018). The total value of the recovered resources for KSA is potentially about US$3 billion/year from 2030 (Table 3). Probably many of the existing WWTPs will have been transformed into RRFs and markets for the recovered resources will be more developed by 2030.

6.1. Water reuse

The most important resource in wastewater often is water, once it has been cleaned to prevent harm to the consumer using fit-for-use treatment (Rittmann & McCarty 2020). KSA uses desalination, an energy-intensive process, with average energy

Table 2 | Capacities of WWTPs in KSA

Region	No. of WWTP [No.]	Treatment capacity [m^3/day]	Sludge production[a] kg-VSS/day	kg-TSS/day	Methane production[a] [m^3/day]	Phosphate[b] [tonne/year]	Ammonium[b] [tonne/year]	Energy demand[c] kWh/day
Riyadh	14	1,315,404	108,082	133,346	32,425	4,801	21,606	789,242
Mecca	8	1,181,615	97,089	119,783	29,127	4,313	19,408	708,969
Medina	3	350,662	28,813	35,547	8,644	1,280	5,760	210,397
Qassim	5	169,300	13,911	17,162	4,173	618	2,781	101,580
Eastern Province	15	1,107,625	91,010	112,283	27,303	4,043	18,193	664,575
Asir	14	169,015	13,887	17,133	4,166	617	2,776	101,409
Tabuk	2	112,500	9,244	11,404	2,773	411	1,848	67,500
Hail	2	45,850	3,767	4,648	1,130	167	753	27,510
Northern borders	3	19,900	1,635	2,017	491	73	327	11,940
Jazan	13	46,765	3,843	4,741	1,153	171	768	28,059
Najran	2	5,230	430	530	129	19	86	3,138
Al-Abha	8	1,440	118	146	35	5	24	864
Al-Jouf	2	36,500	2,999	3,700	900	133	600	21,900
Total	91	4,561,806	374,828	462,441	112,448	16,651	74,928	2,737,084

Source: https://www.stats.gov.sa/en and https://data.gov.sa/ accessed on 13 June 2022.
[a]Estimated from Lenntech webpage: https://www.lenntech.com/wwtp/calculation-summary.htm
[b]Based on typical domestic wastewater composition as described in Chen *et al.* (2020).
[c]Calculated at 0.6 kWh/m^3 as described by Bengtsson *et al.* (2019).

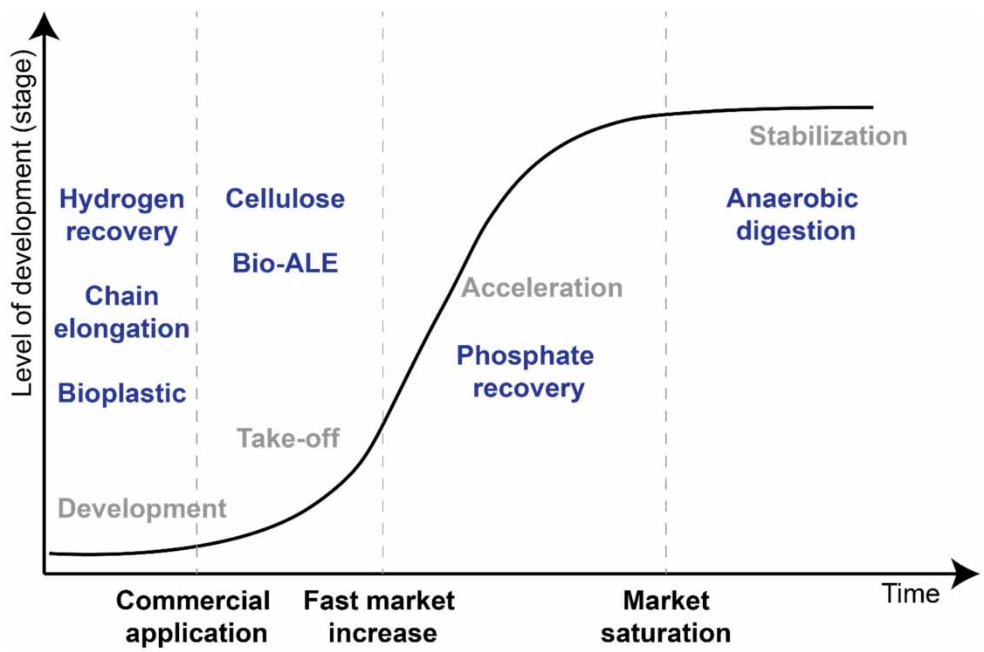


Figure 5 | The level of development for recovery of different resources from wastewater.

consumption of 6 kWh/m^3 (Reddy & Ghaffour 2007; Shahzad *et al.* 2017), to produce freshwater to meet its municipal water demand. The used water is then treated using aerobic wastewater treatment processes such as the activated sludge (AS) process where ~50% of the total energy (0.6 kWh/m^3) (Bengtsson *et al.* 2019) is consumed is for aeration and most of the treated effluent is released back to the sea without reuse. The need for energy for wastewater treatment might drop significantly due

Table 3 | Forecasted rough quantities and values of recovered resources from wastewater in 2030 for KSA

Description	Quantities (2030)	Unit cost (US$)	Revenue (US$ M)
Wastewater treated[a]	2.8 km^3/year	–	
Energy used for treatment[b]	1.68 B kWh/year	0.085/kWh[c]	−143
Water reuse	1.96 km^3/year	1.6/m^3 [d]	3,136
Methane production[e]	69 M m^3/year	0.2/m^3[f]	13.8
Phosphate-P[g]	28 K tonnes/year	0.4 M/K tonnes[f]	11.2
Cellulose	100 K tonnes/year	0.3 M/K tonnes[f]	30
Bio-ALE	0.73 K tonnes/year	2 M/K tonnes[f]	1.46
Total (US$ M/year)			**3,050**

[a]Assuming 100% wastewater will be treated, the amount of wastewater generated by 40 million people (forecasted population of KSA) is estimated at 212.5 L/capita/day.
[b]Calculated at 0.6 kWh/per/m^3 as described by Bengtsson *et al.* (2019).
[c]Electricity tariffs as mentioned on the Saudi Electric website, accessed on 22 June.
[d]Water tariff as mentioned on the Marafiq website, accessed on 22 June 2022.
[e]Methane production from anaerobic digestion was estimated from the Lenntech website, accessed on 22 June 2022. Generated methane can be utilized to offset the energy demand for the treatment of wastewater.
[f]Estimates are based on the number mentioned elsewhere (van Leeuwen *et al.* 2018).
[g]Based on typical domestic wastewater composition as described in Chen *et al.* (2020). Phosphate will be harvested as struvite using chemical precipitation.

to the introduction of more energy-efficient technologies, e.g., AGS (Pronk *et al.* 2015; Ali *et al.* 2019b). This linear water cycle should be changed to a circular water cycle, where the treated effluent should be reused for beneficial purposes such as agriculture and irrigation, groundwater replenishment, industrial processes, and environmental restoration. The average wastewater generated in KSA is estimated at 212.5 L/capita/day (SWPC 2020), roughly generating 2.7 billion m^3/year of wastewater. The Saudi National Water Strategy (NWS) highlights the need for treated sewage effluent reuse, which was 17% in 2016 and to reach 70% in 2030 (SWPC 2020). An increase in reuse will reduce the pressure on non-renewable water resources and decrease dependency on energy-intensive desalination process. However, water reuse will not be able to cover the demand for agriculture and other sectors, so KSA will still rely on desalination, but future desalination plants will be coupled with solar to reduce CO_2 emissions and energy consumption.

Current centralized wastewater networks and treatment plants in KSA cannot handle the increasing population demand for sanitation. KSA has vast water distribution network coverage spanning over 122,780 km in length. Whereas wastewater collection sewer lines are 47,639 km in length which is around 40% of the water distribution network (KSA 2022). Expanding the infrastructure in many cases is impractical due to physical constraints and requires prohibitively expensive capital investment. Currently, 40% of the households in KSA are not connected to the centralized wastewater network. Also, current centralized WWTPs are not designed for recycling wastewater. One approach to address this gap is by proposing new decentralized plants which would also avoid the construction of centralized sewage collection networks and could facilitate treated effluent reuse for the same community. It is proposed to integrate the AGS process with gravity-driven membrane (GDM) filtration to achieve energy-efficient decentralized domestic wastewater treatment and reuse (Figure 6) (Ali *et al.* 2022). The majority of full-scale centralized AGS installations worldwide are in countries where water scarcity is not an issue. To address the water scarcity issue and achieve effluent quality suitable for non-potable reuse, further polishing of the effluent from AGS would be required. Currently, MBR technology based on AS process is the standard technology for wastewater treatment and reuse. AS-MBR plant consumes on average 1 – 2 kWh/m^3, where a large fraction of this energy is used for aeration, filtration process, and scouring of the membranes to minimize fouling (Bengtsson *et al.* 2019). In contrast, AGS technology requires significantly less (0.2 kWh/m^3) energy (Pronk *et al.* 2015) than AS-MBR. Since the GDM process is a self-driven membrane filtration process operated at sub-critical flux, it does not cause frequent fouling and requires no energy input as the process is driven by the natural gravity pressure (Ali *et al.* 2022). Also, AGS technology can greatly reduce footprint by 75%, hence making it suitable for decentralized wastewater treatment and reuse.

The pilot testing of the AGS-GDM unit has now been successfully completed with real wastewater. The AGS-GDM system produced superior effluent quality than the neighbouring full-scale AS-MBR with higher concentrations of NO_3^--N and PO_4^{3-}-P (data unpublished). Currently, the AGS-GDM process is being scaled up under the KAUST Research Translation Program (Near Term Grand Challenge) to specifically tackle the above grand challenges. Under this project, the AGS-GDM unit

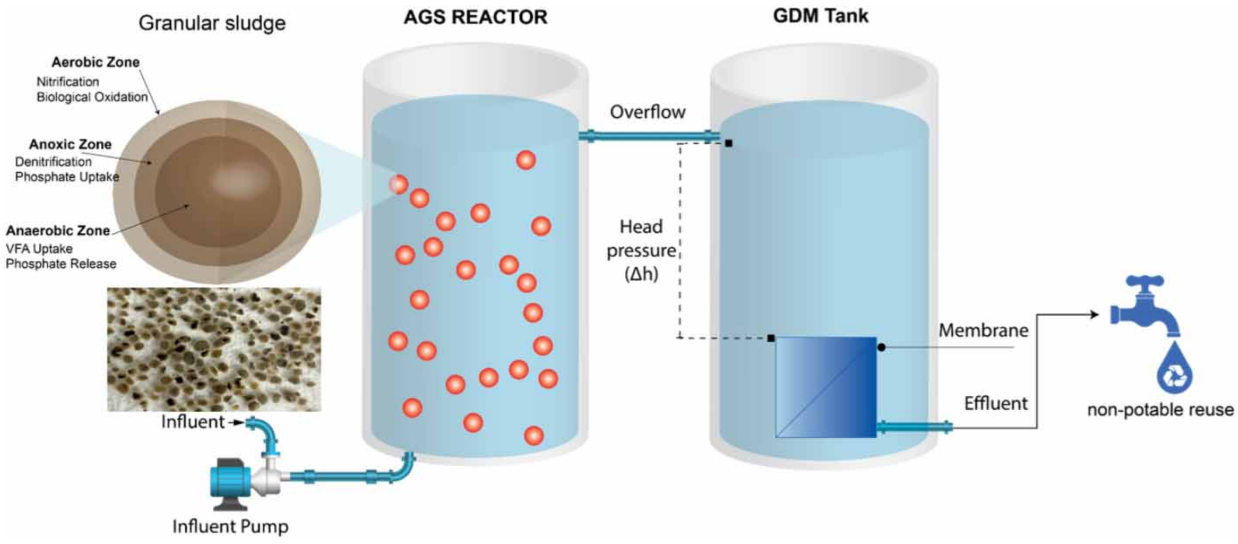


Figure 6 | A schematic illustration of AGS-GDM for decentralized wastewater treatment and reuse. The AGS reactor contains microbial granules. Each granule is made of different microbial layers allowing the removal of different constituents in wastewater. Outside layers (oxic zone) are more exposed to oxygen than inner layers, which are anoxic/anaerobic. The GDM tank is a self-driven membrane filtration process operated at sub-critical flux which does not cause frequent fouling and requires no energy input as the process is driven by the natural gravity pressure.

for wastewater treatment and recycling will be built and demonstrated at a real-world application scale. Also, it addresses many critical aspects, including infrastructure development, water savings, economy, job growth, and impact on the people of KSA. Other technologies that integrate the production of reusable water with energy recovery are discussed in the next section.

6.2. Integrating the production of reusable water with energy recovery from wastewater

Annually, the 91 centralized WWTPs in KSA consume about 1 million MWh–assuming an average-size WWTP requires 0.6 kWh/m^3 of wastewater (Bengtsson *et al.* 2019). These WWTPs have the potential for biogas production of about 112 million m^3/year which can cover almost 40% of the energy consumption of the water authorities (Wan *et al.* 2016; Bengtsson *et al.* 2019). It is estimated that biogas production at 112 million m^3/year leads to a total saving of US$25 million/year (van Leeuwen *et al.* 2018). It will also lead to a reduction in the use of fossil fuels to drive WWTPs.

The current research programme on wastewater treatment aims to achieve a circular economy in wastewater treatment by integrating energy production and resource recovery (energy) into the production of clean water. In this regard, anaerobic microbial technologies hold great promise for resource recovery (energy) from wastewater. As such, microbial processes based on methanogenesis or electrogenesis offer an opportunity to biologically treat the organic carbon in wastewater with the concomitant recovery of energy as methane (methanogenesis) in AD or hydrogen in microbial electrolysis cell (MEC).

In MECs, efficient electroactive bacteria (EAB) such as *Geobacter sulfurreducens* and *Desulfuromonas acetexigens* (Katuri *et al.* 2020; Sapireddy *et al.* 2021), which have a unique respiratory pathway, namely extracellular electron transfer (EET) pathway, transfer the metabolically generated electrons from the oxidation of organic waste to insoluble extracellular electron acceptors such as anode (Figure 7). The bioanode in MECs is electrically connected to a cathode where proton reduction to H_2 occurs using an inexpensive inorganic catalyst (e.g., nickel) (Katuri *et al.* 2019). One key problem in integrating MECs or AD for mainstream urban wastewater treatment is that they do not produce high-quality water suitable for reuse. To address this, MEC and AD are integrated with membrane filtration processes to generate permeate suitable for reuse. The integrated biotechnologies are referred to as anaerobic electrochemical membrane bioreactor (AnEMBR) for the case of MEC (Katuri *et al.* 2014, 2016; Werner *et al.* 2016; Sapireddy *et al.* 2019; El Kik *et al.* 2021) and anaerobic membrane bioreactor (AnMBR) for the case of AD (Wei *et al.* 2014; Harb *et al.* 2015; Shoener *et al.* 2016; Cheng *et al.* 2019). AnEMBR and AnMBR have been demonstrated successfully at the lab-scale for achieving energy-efficient treatment of domestic wastewater while

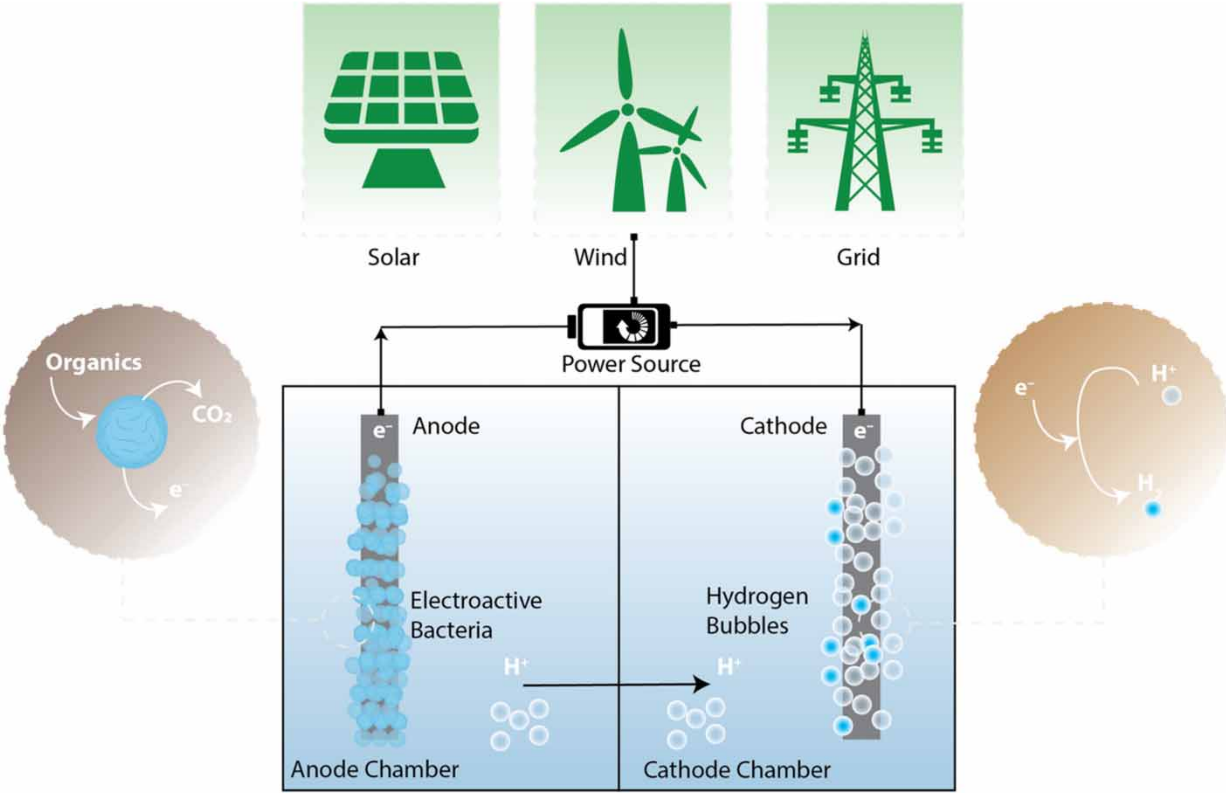


Figure 7 | A schematic representation of a microbial electrolysis cell for wastewater treatment with the recovery of energy. The small voltage (0.8–1.0 V) required to drive the MEC process can be supplied by renewable energy such as solar or wind (Katuri *et al.* 2019).

simultaneously generating good quality water suitable for agriculture reuse (Katuri *et al.* 2016; Werner *et al.* 2016; Cheng & Hong 2017; Harb & Hong 2017; Sapireddy *et al.* 2019; Zaouri *et al.* 2021). However, findings from the lab-scale may not be directly applied to full-scale systems as the environmental and temporal variability in the incoming stream of raw wastewater was not accounted for in the lab studies. Currently, experiments are underway to demonstrate the feasibility of AnEMBR at the pilot-scale and AnMBR at the demonstration-scale (Figure 8) and under real conditions.

Roughly, 500 tonnes of dry waste sludge is produced every day in KSA (Table 2). Off-site landfilling is the current practice for waste sludge management. Waste sludge generated from WWTPs is being collected and transported to the landfilling sites. Trucking waste sludge is costly (each trip costs around US$ 50–75), and results in traffic congestion, air pollution, and GHG emissions (methane) from landfills. Instead, the waste sludge can be used to recover resources such as cellulose, bioplastics, phosphate, and bio-ALE and later sludge can still be digested to produce biogas. Currently, in the KSA, there is only one anaerobic digester operational in a WWTP in Riyadh. The produced biogas (a mixture of CH_4 and CO_2), after desulphurization, is either flared or used for electricity generators in emergencies.

It is pertinent to mention that the conventional AD process often suffers operational instability and low biogas yield, caused by substrate characteristics, short-chain fatty acids (SCFAs) accumulation, and/or ammonium ions (Hobbs *et al.* 2018). MECs could potentially be integrated with existing AD processes to enhance stability and facilitate SCFAs degradation (Hari *et al.* 2016a, 2016b). The MEC-assisted AD (MEC-AD) process successfully avoided SCFA accumulation during waste-activated sludge (WAS) degradation and suggested that exoelectrogens were much more efficient in SCFA degradation (Sun *et al.* 2014). Another advantage of integrating MEC with AD is the enhancement of CH_4 production and purity (Feng *et al.* 2015a, 2015b).

Alternatively, waste sludge production can be minimized by directly cleaning wastewater using AnMBR. Over a course of a 30-week operation, we have observed that our demo-scale AnMBR generates at least 20 times lower volume of sludge compared to the aerobic wastewater treatment process that is operated at the same site and receiving the same type of influent. The AnMBR minimizes the volume of sludge that needs to be disposed of or digested, in turn bypassing the problems

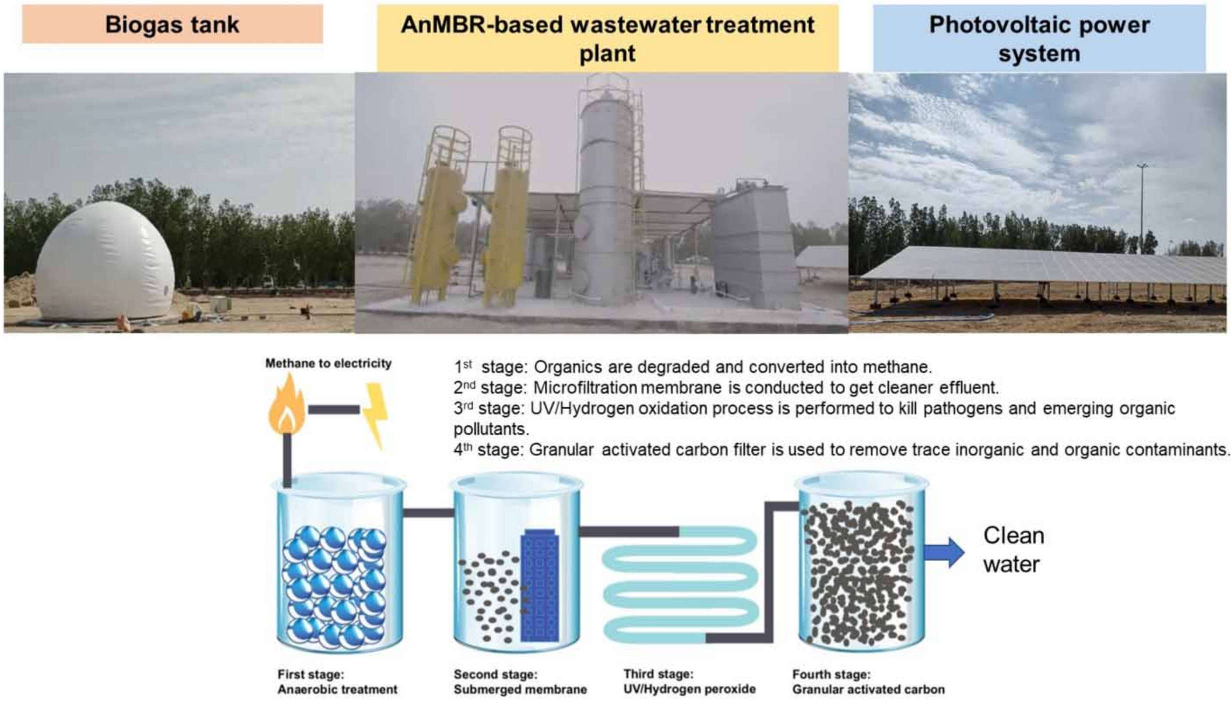


Figure 8 | A schematic representation of the demonstration-scale AnMBR-based wastewater treatment plant that is commissioned and currently under operation in Jeddah, Saudi Arabia. The treatment capacity for this plant is 50 m^3/day and is entirely powered off-grid.

mentioned earlier. Instead, energy is directly obtained by converting the organic carbon in the wastewater to methane. In the demonstration-scale wastewater treatment plant (50 m^3/day capacity), the AnMBR functions as the core technology for carbon removal, while UV/hydrogen peroxide is used for disinfection and further degradation of organic micropollutants (Augsburger *et al.* 2021). As AnMBR cannot remove ammonium and phosphate, these nutrients can either be captured first by biochar to convert into solid fertilizers (see section 6.3) or directly reused for urban farming or green landscapes grown in a controlled system (e.g., blue-green walls, (Prodanovic *et al.* 2017, 2019, 2020)). The nutrients and CO_2 within the biogas may also be suitable to sustain microalgae farms to derive value-added products such as bioplastics, lipids, biomass-based fuels, etc. In a proof-of-concept study, mixed microalgae-bacteria photobioreactors were successfully operated to utilize nutrients that remained in effluents from AnMBR and CO_2 from the biogas (Xiong *et al.* 2018), in turn enhancing the purity of the effluent stream and the produced CH_4.

6.3. Ammonium

Nitrogen is generally present in the form of ammonium or organic nitrogen in wastewater. In KSA, about 75 tonnes of ammonium is wasted every year in the WWTPs (Table 2). Important to realize is that, in order to feed the world's growing population, N_2 in the atmosphere is converted into ammonium for use as a crop fertilizer using the Haber-Bosch process, which is an energy-intensive process (12.1 kWh/Kg NH_3-N), consumes about 7% of the world's natural gas, one of the fossil fuels causing climate change (McCarty *et al.* 2011). The ammonium in municipal wastewater comes from the food we eat, and conventional wastewater treatment for nitrogen removal based on nitrification and denitrification generally converts the ammonium back into N_2 gas at an energy expenditure of 4.6 kWh/kg-N (Cruz *et al.* 2019). The current routes for ammonium removal not only neglect the energy embedded (about 12 kWh/Kg NH_3-N) in ammonium (Trimmer *et al.* 2017) but can also produce N_2O, which is a potent GHG with a 300-fold stronger greenhouse effect than CO_2 and is one of the most dominant ozone-depleting gas (Ali *et al.* 2016). Therefore, there is a need to develop alternative NH_4^+ management approaches that centre on the recovery of energy from NH_4^+ in domestic wastewater rather than dealing with its 'destruction' into dinitrogen (N_2) (Cruz *et al.* 2019).

Recently, it has been demonstrated that freshwater and marine anammox bacteria can oxidize ammonium directly to N_2 using an anode in an MEC as an electron acceptor. The electrons from the oxidation of ammonium are then harvested at the cathode for H_2 generation in MEC (Katuri *et al.* 2019; Shaw *et al.* 2020). A key research programme is to integrate the electro-anammox process with mainstream wastewater treatment to achieve an energy-neutral or possibly energy-positive wastewater treatment (Ali & Okabe 2015; Shaw *et al.* 2020). This can be done by having a two-stage treatment with the anaerobic treatment of organic C by heterotrophic EAB with the recovery of energy as H_2 in stage 1, followed by treatment of ammonium by autotrophic EAB (electro-anammox) with the recovery of energy as H_2 in stage 2 (Figure 9). This process will be coupled with the GDM unit to achieve energy-neutral or (positive) treatment of domestic wastewater while simultaneously generating reclaimed water suitable for non-portable reuse. The proposed process has important implications for the efficient treatment of nitrogen-rich wastewater with energy recovery. This agrees with the emerging interest worldwide for resource recovery from waste streams in the context of a circular economy.

Both AnMBR and AnEMBR do not remove nitrogen (10–50 mg N/L) present in wastewater, which represents an opportunity if they can be concentrated and recovered and then applied as a fertilizer. Given the low concentration of ammonium in domestic wastewaters, it is not economically cost-effective to recover ammonium using existing technologies (Cruz *et al.* 2019). For ammonium recovery to become economically attractive, its concentration in the waste stream should be above 2 g-N/L. One approach to concentrate ammonium from the effluent of anaerobic technologies (i.e., AnMBR or AnEMBR) is by utilizing biochar – produced by pyrolysis of waste organic biomass such as date palm leaves in the absence of oxygen – for adsorbing N in wastewater followed by the application of 'loaded' biochar as a fertilizer. This can be achieved using a configuration for mainstream wastewater treatment where A-stage is specifically designed to maximize the recovery of energy from organic matters in domestic wastewater as methane in AD or hydrogen in MEC, whereas B-stage is mainly dedicated to biological nitrogen removal or recovery (Wan *et al.* 2016; McCarty 2018; Shaw *et al.* 2020). Ammonium in stage B can be recovered through biochar after fine-tuning its material properties via reactor engineering and surface functionalization (Figure 10). Nutrient-loaded biochar can be utilized as a slow-release fertilizer (Zhang *et al.* 2022) that also locks carbon in the soil, thereby combating climate change. In doing so, a net energy-neutral wastewater treatment process can be realized.

6.4. Phosphate

Phosphate (PO_4^{3-}) is a scarce resource on the global scale with limited reserves, especially found in Morocco and China today; almost all the phosphate is mined and used in agriculture. Most of that phosphate ends up in waterways due to

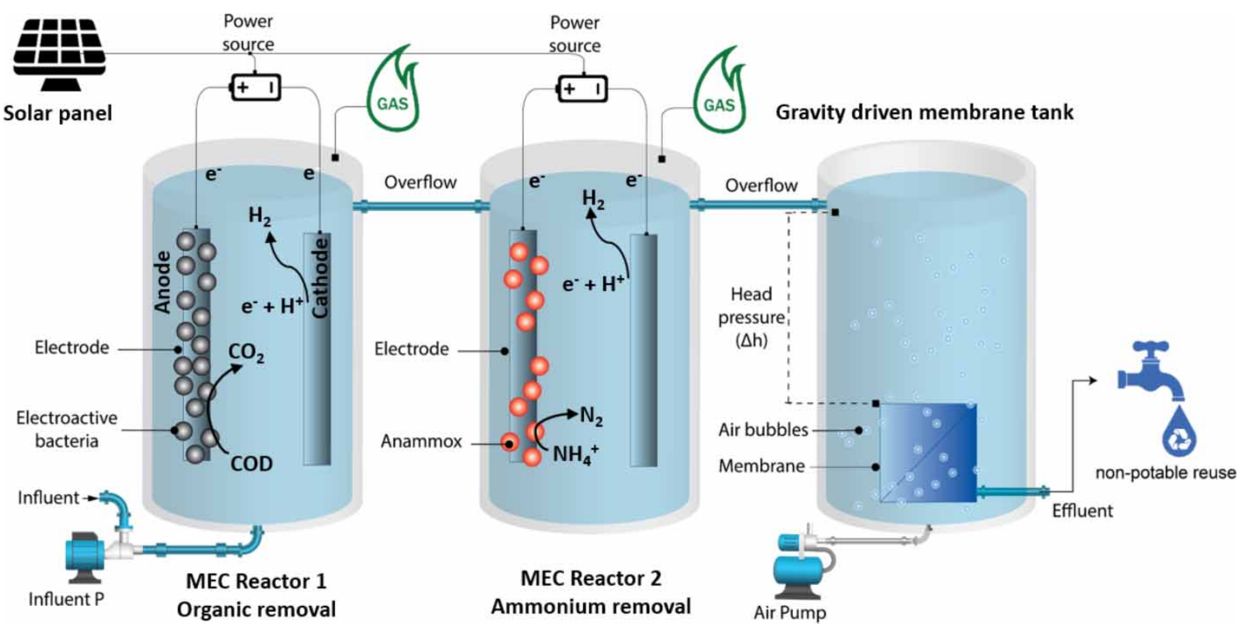


Figure 9 | A schematic illustration of an AnEMBR for wastewater treatment and non-potable reuse with the recovery of energy. In MEC reactor 1, electroactive bacteria on the anode oxidize organics in wastewater and the electrons and protons generated from organic oxidation are converted to H_2 at the cathode. In MEC reactor 2, electro-anammox bacteria oxidize ammonium in wastewater and the electrons and protons generated from ammonium oxidation are converted to H_2 at the cathode.

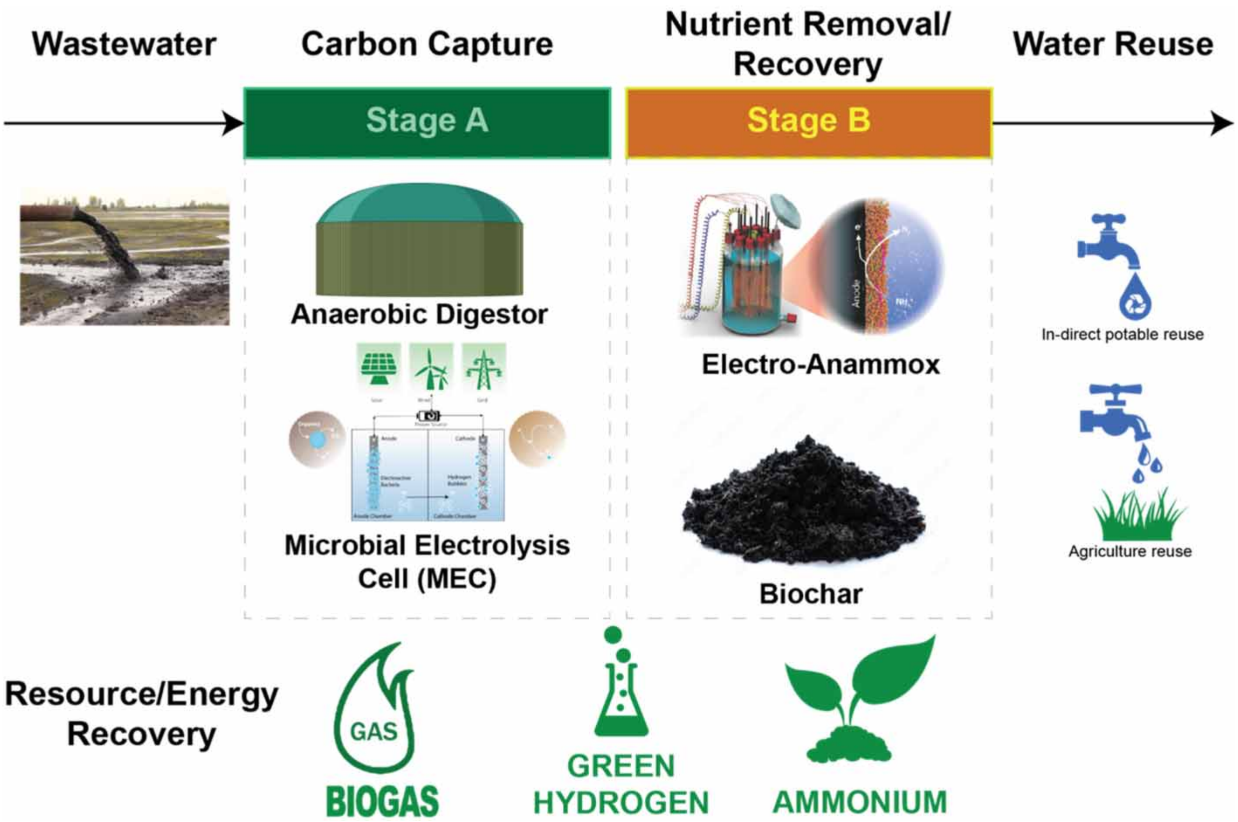


Figure 10 | A schematic representation of a general configuration of the A–B process for wastewater treatment and reuse with the recovery of energy. A-stage is specifically designed to maximize the recovery of energy from organic matters in domestic wastewater as methane in AD or hydrogen in MEC, whereas B-stage is mainly dedicated for nitrogen removal/energy recovery as in electro-anammox or nitrogen recovery using biochar.

run-off and wastewater discharges (Rittmann & McCarty 2020). Phosphate causes eutrophication of surface waters (Morée *et al.* 2013; Rittmann & McCarty 2020). Like ammonium, phosphate in wastewater must be treated to very low concentrations (<1 mg/L) before being discharged to aquatic environments or when treated water is recycled for non-potable reuse. Currently, enhanced biological phosphorous removal (EPBR) is considered the main biological process for the removal of phosphate from wastewater (Dueholm *et al.* 2022). Instead of biological removal through the EBPR process, phosphate can be recovered as, e.g., struvite ($MgNH_4PO_4{\cdot}6H_2O$). In this way, phosphorus becomes available again since the recovered struvite can be applied as a fertilizer. Struvite is formed in digested sludge based on a process with the addition of magnesium chloride ($MgCl_2$). Raw domestic wastewater contains approximately 10 mg-P/L/person/year (Chen *et al.* 2020), which corresponds to approximately 17,000 tonnes of phosphate/year in KSA (Table 2). Recently, a phosphate recovery facility was introduced in a WWTP in Amsterdam and other communities, which can produce 900 tonnes of struvite (van der Hoek *et al.* 2015, 2016). The plant treats approximately 2,000 m^3 sludge/day, while the expected savings are €400,000/year (van der Hoek *et al.* 2016). The savings of this process consist of selling the struvite, lowering the sludge handling costs, and better sludge dewatering. Extrapolated for KSA, the recovery of phosphate could generate approximately US$11.2 million/year from the year 2030 (Table 3).

6.5. Cellulose

Cellulose is a material which ends up in sewage due to the use of toilet paper, and cellulose can be recycled from toilet paper (Ruiken *et al.* 2013). This recovered cellulose can be used in road construction, but further markets need to be developed (Crutchik *et al.* 2018). A person uses an average of 10 kg of tissue paper/year (Ruiken *et al.* 2013), which means that the total potential volume is approximately 420,000 tonnes/year in KSA. Nevertheless, not all tissue paper can be recovered at WWTPs. It is estimated that about 25% of cellulose can be recovered with the introduction of fine-sieving at WWTPs

(Roest 2017), which will lead to approximately 100,000 tonnes/year. Although there are currently no revenues from cellulose recovery at all, as considerable investments are necessary, the potential revenue is interesting due to the expected price of this material, i.e., approximately US$300/tonne (van Leeuwen *et al.* 2018).

In the context of digesting cellulose to produce methane, the fermentation process suffers from low yields, and instability caused by the accumulation of acids from the degradation of complex substrates such as cellulose (Lusk *et al.* 2018). Coupling fermentation with MECs could be a viable approach for efficient biogas production from renewable biomass (Lu & Ren 2016). Several studies reported the integration of MEC with fermentation for cellulose waste degradation (Lalaurette *et al.* 2009; Wang *et al.* 2011; Lusk *et al.* 2018).

6.6. Alginate-like exopolymers (bio-ALE)

Alginate is a naturally occurring anionic polymer. It is a polysaccharide, typically obtained from brown seaweed and has been extensively investigated and used for many biomedical applications which include wound healing, drug delivery, and tissue engineering due to its biocompatibility, low toxicity, and relatively low cost (Roest *et al.* 2015). Bio-ALE is an alginate-like polymer of sugars and proteins and can be used in agriculture and horticulture, paper industry, medical, and construction industries. Bio-ALE can be applied as fibres, gel, or foam. Fibres can be used for the production of absorbing tissues, gels can be used as glue for the production of fertilizer pellets, and foam can be used for the production of fire-resistant boards. The liquid version can be used for thickening inks, improving paper quality, and increasing the quality of curing concrete (Roest *et al.* 2015). The first bio-ALE production installations were built in Zutphen and Epe in 2019 in the Netherlands. In a field test, it was demonstrated that 0.2 kg bio-ALE can be produced per kg of Nereda AGS (HaskoningDHV 2017) and a tonne of ALE has market values of approximately US$ 2,000 (van Leeuwen *et al.* 2018). The extraction of bio-ALE from AGS can be considered up-cycling because a more valuable product is produced from waste. Recently, the National Water Company (NWC) tender a Nereda plant of 50,000 m^3/day capacity in Jeddah. It is expected that more WWTPs in KSA will be retrofitted or upgraded to Nereda technology by 2030. Assuming the total capacity of Nereda plants would be 150,000 m^3/day by 2030, it would potentially produce 730 tonnes bio-ALE (from 3,650 tonnes of excess sludge)/year. The sale of bio-ALE would generate revenue of about US$1.46 million/year by 2030 (Table 3).

6.7. Bioplastic

Bioplastic can be produced from sewage sludge as a form of up-cycling. Bioplastics are formed using a complicated process during which volatile fatty acids (VFAs) are produced first and then later fed to microbes which produce the building blocks for bioplastics (i.e., PHA). There have been some experiments and tests that showed an average extraction amount of 30 g-PHA/100 g of biomass was achieved with 98% purity (de Souza Reis *et al.* 2020). The production cost of this material, however, is currently still rather high, and it is twice as much as the regular market price. Furthermore, there is no available stable industrial production process yet (van Leeuwen *et al.* 2018). Currently, plastics are produced through petroleum products made from fossil fuels. In future, there will be more demand for bioplastics to minimize reliance on fossil fuel-based plastics.

7. SUMMARY AND OUTLOOK

The existing centralized wastewater-related infrastructure is not able to be modified easily. The creation of new RRFs from scratch is capital intensive compared to upgrading existing centralized WWTPs to RRFs. Therefore, upgrading or retrofitting existing centralized facilities would be the most feasible route at the beginning to achieve a circular economy in the water sector. Once critical knowledge and experience have been gained, resource recovery technologies would also be implemented for newer and smaller-scale installations.

Water reuse should be preferred to achieve circularity. Currently, a centralized approach is used for wastewater management, collection, and treatment. Upgrading centralized WWTPs with water reclamation and reuse facilities could support the increase of water reuse in KSA. However, many centralized WWTPs are located far away from city centres and in areas where water demand for treated effluent is low. In such cases, physical infrastructure (such as pipelines) is needed to transport the treated effluent to areas with high water demand. There is a lack of centralized infrastructure for water reuse and building centralized water reuse infrastructure could be capital intensive. Therefore, modular, adaptive, and/or decentralized approaches should be implemented using sustainable technologies such as AGS-GDM, AnEMBR, and AnMBR, which could enable treated water reuse at a neighbourhood scale. Implementation of a modular, adaptive, and/or decentralized approach for newer installations would certainly promote water reuse and help to achieve the 2030 water reuse target (70%) by the Kingdom of Saudi Arabia.

There are already established technologies for the recovery of CH_4, phosphorus, cellulose, and bio-ALE from sludge, which could be easily integrated into existing installations. As mentioned above, conventional AD or modified MEC-AD could be easily integrated into existing facilities to recover CH_4 from waste sludge. However, it should be highlighted that there is no infrastructure available for CH_4 distribution and it could be expensive to build such infrastructure. Therefore, the generated CH_4 should rather be utilized to offset the energy requirement of the wastewater treatment to make the system more energy-efficient or energy-neutral.

ACKNOWLEDGEMENTS

This work was supported by the Center Competitive Funding Program (FCC/1/1971-33-01, FCC/1/1971-44-01), Near Term Grand Challenge Funding Program (REI/1/4254-01-01), Research Translation Funding Program (REI/1/4223-01-01), and Impact Acceleration Funding Program (REI/1/4224-01-01) from King Abdullah University of Science and Technology.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 29 June 2022; accepted in revised form 11 August 2022. Available online 1 September 2022