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Reclaimed water in Taiwan: current status and future prospects

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Abstract

According to the Taiwan Water Resources Agency, Ministry of Economic Affairs, the average water demand shortage is 530.6 million m^3 yr^{-1} during the period of 2011 to 2019, and the situation will worsen in the near future due to global climate change. Therefore, reclaimed water has been an important new water source in Taiwan, particularly for industrial consumers such as high-tech industries in Science Parks. In order to meet the targeted reclaimed water supply of 1.32 million m^3 d^{-1} (CMD) in 2031, Taiwan is focusing on two major reclaimed water sources, including reclaimed water from high water-consuming industries and municipal wastewater treatment plants. This report reviews current technologies used for reclaimed water including units for pretreatment, desalting, polishing, and reclamation. Case studies in Taiwan including reclaimed water from high water-consuming industries such as thin film transistor-liquid crystal display (TFT-LCD) and semiconductor industries, as well as from municipal wastewater treatment plants are presented. The TFT-LCD company Innolux and semiconductor company Advaned Semiconductor Engineering have implemented total recycled water system to recycle and reclaim wastewater from manufacturing processes, achieving a total recycled water of 290 million m^3 yr^{-1} with about 97% recovery and 3.5 million m^3 yr^{-1} with 80% recovery, respectively. The Fengshan reclaimed water treatment plant produces 40,436 CMD reclaimed water from municipal wastewater for the China Steel Cooperation's steel-making processes, at an overall operation and maintenance cost of 11.5 NT dollars m^{-3}. Meanwhile the Yongkang plant produces 15,500 CMD of reclaimed water for semiconductor and TFT-LCD manufacturing processes at an overall operation and maintenance costs of 25.8 NT dollars m^{-3}, which is due to low urea and boron limits requested by the user. Finally, challenges and future prospects for promoting the use of reclaimed water to meet the targeted supply in 2031 will be discussed.

Keywords Reclaimed water, High-tech industries, TFT-LCD, Semiconductor, Municipal wastewater

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1 Introduction

Taiwan, located in a subtropical region, is known for its warm and humid climate with abundant rainfall. Additionally, the country experiences typhoons almost every year. Taiwan receives an average rainfall of approximately 2,542 mm yr^{-1}. Which is 2.6 times higher than the global average. It may be surprising, but Taiwan faces a dilemma of insufficient water resources despite its abundant rainfall and humid climate. Taiwan's short and rapid rivers, coupled with the impacts of global climate change and natural disasters like droughts and torrential rains, have led to a situation where the frequency of abundant or drought year has shortened from decades to just a few years. Since 2002, which was the driest year in Taiwan history, the country has experienced several drought years, including 2011, 2014, 2018, 2019, and 2020. 2021 brought a severe drought to Taiwan, which was described as a "once-in-a-century" event due to its severity [1].

As of 2020, the Taiwan Water Resources Agency (TWRA) under the Ministry of Economic Affairs (MOEA) reported that the existing reservoir had a siltation ratio of 23%, which reduced their effective capacity to 1,984 million m^3 [2]. Furthermore, finding a suitable location for the new reservoir faces challenges due to the environmental concerns and public skepticism towards large-scale projects. The TWRA has reported an average water demand shortage of 530.6 million m^3 yr^{-1} from 2011 to 2019, and predicts that this shortage will become more severe in the future [1].

In 2004, the Water Resource Protection Strategy was approved by the Taiwan National Development Council of the Executive Yuan to address the severe water shortage situation caused by climate change, as part of the "Agenda for 21st Century in Taiwan: Vision and Strategic Plan for National Sustainable Development" [3]. It emphasized the importance of a water resource policy equally emphasizing on water conservation, finding new water sources, strengthening water management, and promoting the recycling and reusing wastewater. In 2009, Taiwan's Executive Yuan approved the revised "Sewage Sewer Development Program" to promote the water reclamation from public sewage wastewater treatment plants. The TWRA established in 2010 and later revised in 2016 the guidelines stating that reclaimed water is not suitable for human consumption and should be kept away from human contact [4]. Therefore, Taiwan uses reclaimed water as a new water source for industrial consumers, especially high-tech industries in Science Parks, since they are willing to pay a higher price for secure water supply.

Taiwan MOEA announced the Reclaimed Water Resources Development Act in 2015 and later amended in 2022 [5], which aimed to provide new water resources for industrial water consumers by recycling wastewater. The Reclaimed Water Resources Development Act in Taiwan requires industrial consumers to use a certain percentage of reclaimed water depending on water undersupply severity at new industrial consumers' location when applying for a water consumption plan to MOEA. The requirement for industries to use reclaimed water in areas with severe water undersupply forces them to search for nearby reclaimed water sources. The Act prohibits the use of reclaimed water for drinking and by the food and pharmaceutical industries. Reclaimed water quality standards for industrial use are set by the central competent authority and the reclaimed water used for such purpose must be complied with. Table S1 in Supplemental Materials outlines the guidelines and quality standards for using reclaimed water in Taiwan [5].

2 Reclaimed water sources

Taiwan's Executive Yuan is focusing on two major sources of reclaimed water to meet the increasing demand, namely reclaimed water from high water-consuming industries and municipal wastewater treatment plants. They aim to supply 1.32 million CMD of reclaimed water by 2031, with 0.77 million CMD from municipal wastewater treatment plants, 0.45 million CMD from high water-consuming industries, 0.05 million CMD from industrial park wastewater treatment plants, and 0.05 million CMD from domestic water consumers [6].

2.1 Reclaimed water from high water-consuming industries

The majority of industrial water is utilized for cooling, boiler, manufacturing process, domestic and miscellaneous water purposes. The TWRA reports that industrial water consumption in Taiwan accounts for 10% of the total annual water consumption, which is approximately 1.63 billion m^3 [7]. The characteristics of industrial wastewater can vary significantly depending on the type of industry and manufacturing processes used. Industrial wastewater effluent typically contains organic substances, suspended solids (SS), heavy metals or trace amounts of toxic substances, as summarized in Table S2 [6].

Since 1996, the TWRA has been providing water conservation consultation services to industrial consumers in order to encourage better water recovery practices. Many industries have embraced the concept of water management and improved their water usage efficiency, particularly for cooling, boiler, and manufacturing process water, with the support of government promotion. The average water recovery percentage for industrial consumers is shown in Fig. S1. It is expected that the industrial water recovery percentage will increase to 75% by 2030 [8].

Industrial reclaimed water in Taiwan primarily comes from the on-site treatment of industrial wastewater within factories. Unlike Science Parks and new industrial parks, existing industrial parks are not subject to regulation on industrial water reclamation rate from manufacturing processes. The regulations on water reclamation percentages require > 85% for manufacturing processes, > 75% for the entire factory, and < 70% for wastewater discharge for the factories in the Science Parks. However, these regulations only apply to newly developed industrial parks, and not to existing ones [9]. At present, the majority of reclaimed industrial water is primarily utilized for cooling water, boiler water, manufacturing process water, and miscellaneous purposes like plant watering and road sprinkler within the factories. Nearly all of the reclaimed industrial water is supplied for internal use within the industrial parks, with the exception of a few instances where it has been approved by the Taiwan EPA for small-scale agricultural irrigation purposes.

2.2 Reclaimed water from municipal wastewater treatment plant

The construction of a reclaimed water treatment plant was accelerated in 2012 by the Construction and Planning Agency (CPA) of Taiwan Ministry of Interior and the Kaohsiung City Government due to the increased water demand from the China Steel Corporation (CSC) in the Linhai Industrial Park. The first reclaimed water treatment plant in Taiwan was selected to be the Fengshan plant, which treats 85,000 CMD of wastewater collected from the Fengshan and Niaosong District areas in Kaohsiung City. After extensive negotiation and collaborative efforts, the Fengshan reclaimed water treatment plant began supplying 25,000 CMD of reclaimed water to the CSC on August 22, 2018. The supply was later increased to 45,000 CMD on August 22, 2019. The Fengshan reclaimed water treatment plant sets a benchmark for promoting the use of reclaimed water from municipal wastewater [10]. Table S3 shows that municipal wastewater treatment plants in Taiwan, produce good quality effluent water that can be used as potential sources of reclaimed water. Table 1 summarizes the current status of 11 municipal wastewater reclamation plants in Taiwan at different stages, including planning, contracting, construction, and operation [10]. The Fengshan and Linhai reclaimed wastewater treatment plants in Kaohsiung, as well as the Yongkang reclaimed water treatment plant in Tainan, currently supply a total of 86,000 CMD of reclaimed water. This amount is set to increase significantly, with a total projected reclaimed water supply of 289,000 CMD in 2026.

3 Technologies for reclaimed water

Due to a significant increase in water demand, treated wastewater effluents are being considered as an alternative water source globally. The treatment of wastewater can vary depending on factors such as the type of wastewater and intended usage of treated water. Figure 1 provides a general overview of the four main stages of wastewater treatment: pretreatment, desalting, polishing, and reclamation [11, 12]. The pretreatment is the initial stage and is similar to traditional wastewater treatment process. The primary goal is to remove SS and to reduce the level of contaminants such as organic matters and remaining chemicals. The second stage involves separating most of the dissolved ions from water. The

Table 1 Current status of the 11 municipal reclaimed wastewater treatment plants

Item	City	Reclaimed wastewater treatment plant	Stage	Water supply (m^3 d^{-1})	Water supply schedule	Current situation
1	Kaohsiung	Fengshan	Operation	45,000	2019	water supply in operation
2	Kaohsiung	Linhai	Operation	33,000	2021	water supply in operation
3	Tainan	Yongkang	Operation	15,500	2021: 8,000 m^3 2023: 15,500 m^3	water supply in operation
4	Taichung	Fukuda	construction	58,000	2026	in the process of being designed
5	Tainan	Anping		37,500	2022: 10,000 m^3 2024: 37,500 m^3	The reclaimed water plant is under construction
6	Taoyuan	Taobei	outsourcing	40,000	2025: 25,000 m^3 2027: 40,000 m^3	BTO model is applying for tendering
7	Taichung	Shuinan		10,000	2024	The investment invitation is completed, and negotiations are underway for the contract
8	Hsinchu County	Zhubei	planning	10,000	2029	Zhudong Factory and Keya Factory are currently undergoing feasibility assessments
9	Taichung	Toyhara		10,000	2028	Central Taiwan Science Houli Park has a water demand, and the city government is evaluating it
10	Tainan	Rende		10,000	2024: 10,000 m^3	In October 2021, a water exchange contract and a reclaimed water use contract were signed
11	Kaohsiung	Nanzi		20,000	2027	The Gangqiao Plant is under planning, and the city government is also conducting a feasibility assessment for it

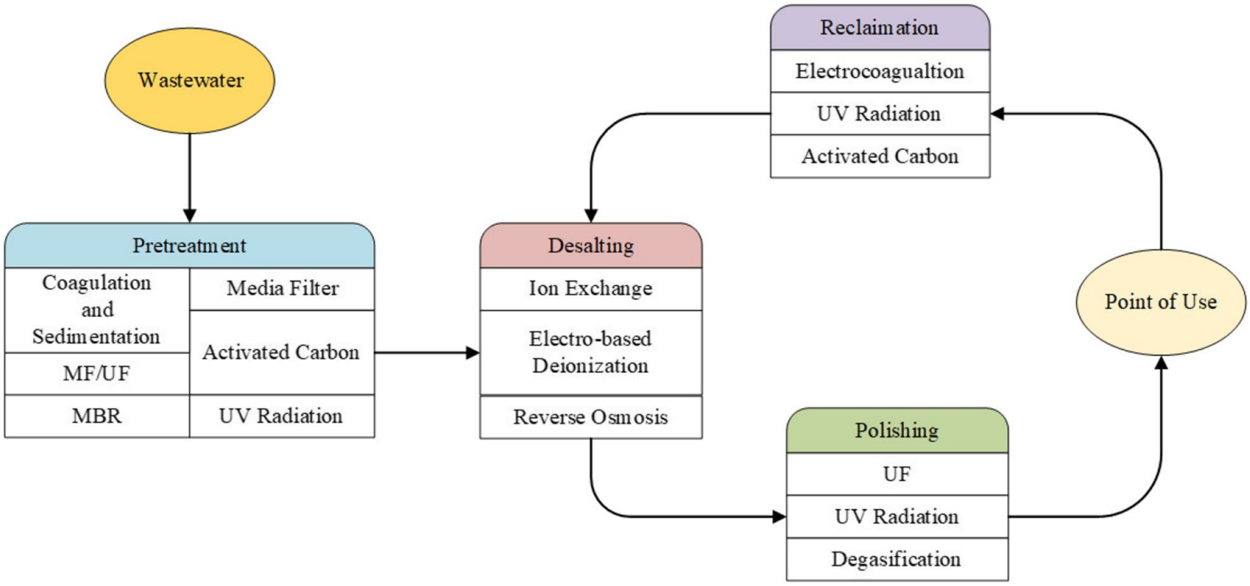

Fig. 1 The options of processes in four typical stages for water reuse

polishing stage follows, which further enhances the quality of the treated water. Finally, more and more industries are adopting the practice to reclaim used or point-of-use water on their premises. This approach involves a process similar to the initial pretreatment stage.

Typically, the treatment processes chosen for water reclamation are based on the intended use of the reclaimed water and the desired water quality for that specific purpose. For example, indirect water reuse such as groundwater recharge might only require adequate pretreatment, while food industry or drinking water reuse needs post-disinfection [13]. As for high-tech industries like semiconductor, display, memory, ultrapure water is essential and require integrated systems that involve all four stages of water treatment.

3.1 Pretreatment

Traditional wastewater treatment primarily aims to meet the discharge standards, while, pretreatment for water reuse focuses on removing factors that may interfere with subsequent treatment processes. Primary water treatment processes that reduce turbidity, such as coagulation and sedimentation [14, 15], media filter, activated carbon and so on [16] can be utilized in the pretreatment stage for water reuse. In chemical mechanical polishing (CMP) wastewater treatment, coagulation and media filtration are commonly used to remove turbidity, while activated carbon is employed to address issues related to organics, color and/or chlorine. Coagulation is a useful process for removing hardness from water, specifically calcium and manganese ions. An ion exchange column can also be employed to further reduce hardness.

Although Ultraviolet (UV) radiation is an effective choice for pretreatment to reduce fouling on the Nanofiltration/Reverse Osmosis (NF/RO) membrane [11], it was initially applied as an oxidation and/or disinfection process in polishing stage. UV radiation is commonly used in the pretreatment stage to oxidize organic matter. Medium-pressure lamps with a central wavelength of 185 nm (UV_{185}) are typically used, which produce hydroxyl radicals and H_2O_2 as oxidants [17]. H_2O_2/UV oxidation has been shown to mitigate membrane flux reduction caused by membrane fouling and improve the membrane cleanability [18]. Harif et al. [19] observed that the use of medium-pressure UV as a pretreatment unit reduced the accumulation of extracellular polymeric substances on RO membrane and decreased the diversity of biofilm by over 30%.

Microfiltration (MF) and/or ultrafiltration (UF) are commonly used membrane techniques to remove SS. The membrane bioreactor (MBR), which combines biological and membrane units, has gained popularity in recent decades due to its ability to produce high-quality effluent with lower levels of SS and organic pollutants. MF/UF can be directly applied to industrial wastewaters that have low SS or CMP wastewater that contains only nanoparticles [20]. In low-strength wastewaters with chemical oxygen demand (COD) < 30 mg L^{-1} and SS < 15 mg L^{-1}, UF can remove almost 100% of SS and 40% of COD [21]. MBR can be used for treating wastewaters with high levels of organic pollutants, such as those generated in thin film transistor-liquid crystal display (TFT-LCD) and semiconductor industries, petrochemical industry, and food industry. An anoxic/oxic (A/O) MBR can be utilized for nitrogen removal from wastewaters containing organic nitrogen and/or ammonia. The innovative NEWater system in Singapore is an example of successful water reuse from treated domestic sewage, using MF/UF as a pretreatment process. A pilot-study showed that replacing the MF/UF followed by an activated sludge system with a MBR for pretreatment increased the RO membrane's permeate flux by 30% [22]. In general, MBR technology as a pretreatment unit can be an effective replacement for traditional secondary wastewater treatment in limited land use scenarios, due to its small footprint.

3.2 Desalting

The desalting process, is a crucial step in producing ultrapure water, with the goal of achieving an electrical resistivity above 10 MΩ cm, which is equivalent to an ion strength of around 50 μg L^{-1} [12, 16]. In 1980s, two-bed ion-exchange systems were commonly used, but today, RO has replaced them as the most widely-applied techniques for water purification. RO process not only removes dissolved ions or total dissolved solids (TDS), but also reduces the levels of organic matter, measured by COD/total organ carbon (TOC). Furthermore, the RO process typically maintains a recovery rate of above 70%. Consequently, poor particle control in the feed water can result in frequent membrane scaling/fouling during water treatment operation. To maintain stable performance in RO processes, fouling indices such as silt density index and modified fouling index (MFI) have been used for decades to evaluate the quality of the feed water. While commonly used in practice, they are not always reliable predictors of RO membrane fouling since they are evaluated using a membrane with 0.45 μm. As a result, these indices may fail to accurately predict fouling in many cases [23]. Alternatively, Zhan et al. [24] successfully used UF as a proxy unit for measuring MFI, which allowed for stable operation of an RO process at pilot-scale for seven months. To reduce the frequency of fouling and ensure effective removal of both silica and fluoride, the pH of feed water in some semiconductor factories is adjusted to above 9.5. However, this approach should be used with caution as increased pH by adding alkaline chemicals can lead to a rise in conductivity, potentially impacting the osmotic pressure of the feed water.

New electro-based deionization processes, such as electrodeionization, electrodialysis reversal (EDR), and capacitive deionization, are emerging as viable options for desalination [12, 25]. EDR is typically utilized for treating wastewater with high conductivity/TDS, and its membrane has greater resistance to silica, colloidal organics, and bacteria than that of RO membrane. EDR can also be utilized to concentrate the reverse osmosis reject in multi-stage RO system before feeding the evaporator due to its lower energy consumption compared to RO when facing high TDS feed water.

3.3 Polishing

One of the primary goals of the polishing stage in water treatment is to suppress the growth of microbes. Research has revealed that even after flushing the storage tank with nitrogen gas, bacteria and biofilm can still be detected in the majority of units during the production of ultrapure water [26]. Apart from the utilization of UF, advanced oxidation process (AOP) such as H_2O_2, ozonation, and/or UV radiation [12] are commonly employed for disinfection. However, it is crucial to note that post-degasification is required to manage the dissolved gases [27]. In the polishing stage of water treatment, the application of UV radiation is dependent on its intended purpose. For disinfection purposes, a low-pressure lamp that emits UV radiation at a central wavelength of 254 nm (UV_{254}) is commonly used. Alternatively, UV_{185} can be used to oxidize any remaining TOC in the water, particularly those with low molecular weight (less than 100 Da) and/or low TOC concentration such as in the range of μg L^{-1} [28]. Zhao et al. [29] conducted a study comparing different units in ultrapure water production process and found that using multi-wavelength $UV_{185/254}$ was more effective in reducing TOC than using UV_{254} or UV_{185} alone. As a result, the multi-wavelength approach successfully reduced the TOC levels from 370 to less than 5 μg L^{-1}. Various degasification methods, such as vacuum degasifier, membrane degasifier, and catalytic resin, can be employed to remove dissolved gases, including O_2 and CO_2, from treated water [12].

3.4 Reclamation

In recent years, the concept of circular economy has gained significant attention, and reclamation has emerged as a crucial stage in this process. When ultrapure water is used in semiconductor manufacturing, scaling during the RO process can be a significant concern, as silica removal becomes a critical aspect of the reclamation stage. If fouling in the water treatment system is primarily caused by silica, then the use of a strong cleaning solution such as ammonium bifluoride may be the only viable option for removal. However, it is essential to note that such solutions can be aggressive and may cause damage to the membrane [30]. In addition to using anti-foulants to prevent silica scaling on RO membrane, electrocoagulation has been shown to effectively remove 80% of silica in the feed water, with a hydraulic retention time of just 30 min [31].

Solvents are frequently used in TFT-LCD and semiconductor industries, and they can present in the used process water following the washing step, which necessitates careful consideration during the wastewater reclamation process. Various solvents, including isopropyl alcohols (IPA), methanol, urea, and others, tend to have low molecular weight and zero surface charge properties. These characteristics can make them difficult to be degraded, particularly when they are present in low concentrations [17]. In a study by Choi and Chung [32], it was found that applying 20 μM of persulfate during UV radiation resulted in a significant 90% removal of urea at a concentration of 1.65 μM. The research suggests that the production of sulfate radical may play a vital role in the breakdown of urea. UV_{185} can effectively treat methanol and IPA, and Choi and Chung's [28] research has indicated that TOC removal can be positively correlated with both dissolved oxygen concentration and UV intensity. In the semiconductor industry, wastewater may contain H_2O_2, which can cause membrane degradation and subsequently decrease the lifespan of the membrane. Using activated carbon is a highly effective approach to react with H_2O_2, resulting in a reduction in its concentration. This method can also simultaneously remove both chlorine and TOC [33].

4 Case studies

4.1 Reclaimed water from high water-consuming industries

To comply with regulations requiring water reclamation rates of at least 85% for manufacturing processes and 75% for the entire factory, companies in Science Parks have been implementing water usage strategies such as reducing, reusing, and recycling wastewater. High water-consuming industries, such as the TFT-LCD and semiconductor industries, are particularly proactive in these efforts.

4.1.1 Innolux Corporation reclaimed water

Innolux operates 14 plants in Taiwan producing comprehensive display products, including large, medium and small sized TFT-LCD panels and touch panels. They categorize their wastewater into 35 distinct types, based on the chemicals used in their manufacturing processes. These wastewaters contain a variety of substances, including F^-, N, P, organics, inorganics, acids, and bases, among others [34]. Innolux employs various treatment units, such as physical, chemical, biological, and combined units, to treat their separately collected manufacturing process wastewaters, based on their chemical characteristics. This approach allows for chemical recovery, wastewater treatment, and reuse. In 2021, the Innolux achieved a 97.2% recovery rate from their manufacturing processes, resulting in a total of 290 million m^3 of recycled water. The water balance diagram depicting Innolux's manufacturing processes located in the Southern Taiwan Science Park is presented in Fig. 2 [34].

Various treatment units, such as coagulation/flocculation/sedimentation, activated carbon filter (ACF), multimedia filter (MMF), bag filter, biofilter, resin, MBR, NF, and RO, are employed to obtain the optimal treatment train for specific wastewaters from different manufacturing processes, achieving the desired reclaimed water quality, as shown in Fig. 3. To meet regulations for wastewater discharge in the Southern Taiwan Science Park, efficient nitrogen removal is required for high organic wastewater containing high concentrations of dimethyl sulfoxide (DMSO) and organic nitrogen solvent monoethanolamine (MEA), both in the reclaimed water and rejected wastewater. Studies have shown that MBR systems can effectively remove MEA and DMSO, achieving more than 70% total nitrogen removal [35, 36], despite the inhibition of nitrification due to dimethyl sulfide produced from DMSO biodegradation under anaerobic condition [37, 38].

4.1.2 AU Optronics (AUO) Corporation reclaimed water

AUO Corporation collects wastewater separately based on the chemical properties used in their manufacturing processes. AUO utilizes various treatment units, such as physical, chemical, biological, and combination methods, to treat their wastewaters depending on their characteristics, aiming for efficient treatment and reuse. AUO achieved a total recycled water of 138 thousand m^3 in 2021, with 94.5% of the water being recovered from manufacturing processes. The water balance diagram for the AUO manufacturing processes in the Longtan Industrial Park in Taoyuan is shown in Fig. 4 [39].

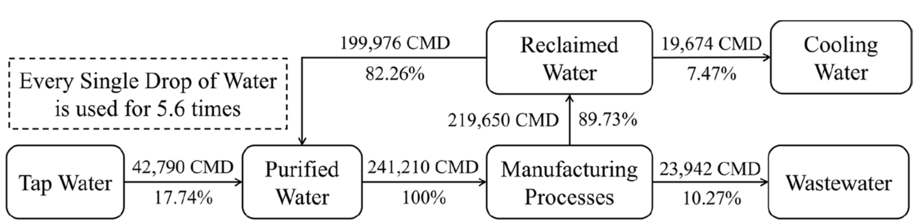

Fig. 2 The water balance diagram for the Innolux manufacturing processes in the Southern Taiwan Science Park

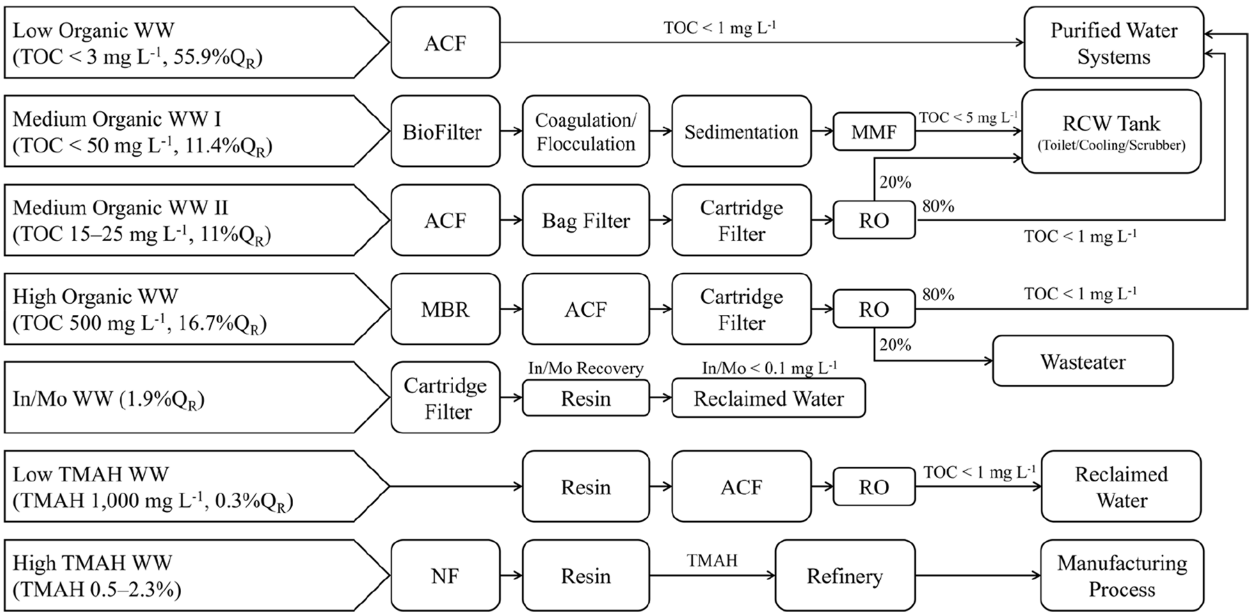

Fig. 3 Reclaimed water from different manufacturing processes in Innolux

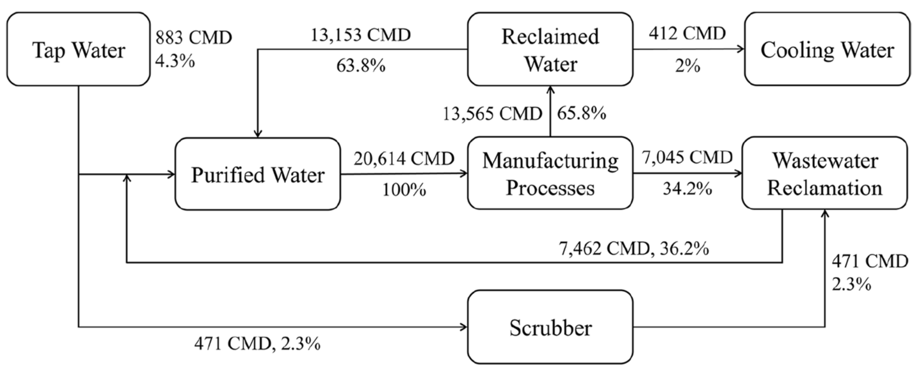

Fig. 4 The water balance diagram for the AUO manufacturing processes in the Longtan Industrial Park in Taoyuan

Different treatment units are used by AUO for the reclaimed water from various manufacturing processes, as illustrated in Fig. 5. These include coagulation/flocculation/sedimentation, bag filter, resin, MBR, EDR, and RO. These units are tailored to obtain the optimized treatment train for specific wastewater, achieving the desired reclaimed water quality.

AUO uses a combination of pH adjustment, resin, EDR, and RO, to recycle resin regeneration wastewater, achieving an 80% recovery and improving overall reclaimed water recovery to 92%. In addition, the rejected water from RO is recycled using EDR and significantly reduced from 35 to 7% (Fig. S2). The rejected water from EDR was treated using mechanical vapor recompression (MVR) (Fig. S3) to achieve zero liquid discharge goal.

4.1.3 Advanced Semiconductor Engineering (ASE) Technology Holding reclaimed water

ASE Technology Holding offers semiconductor manufacturing service in assembly and test, including front-end engineering test, Wafer probing, IC packaging and modules, system and broad integration, electronic design and manufacturing services. The ASE collects wastewater based on their chemical properties used in manufacturing processes. For the purpose of efficient chemical recover, wastewater treatment and reuse, ASE utilizes various treatment units, including physical, chemical, biological, and combined methods to treat separately collected wastewaters depending on their characteristics. In 2021, ASE achieved a total of 3.5 million m^3 of recycled water, recovering about 80% of water used in

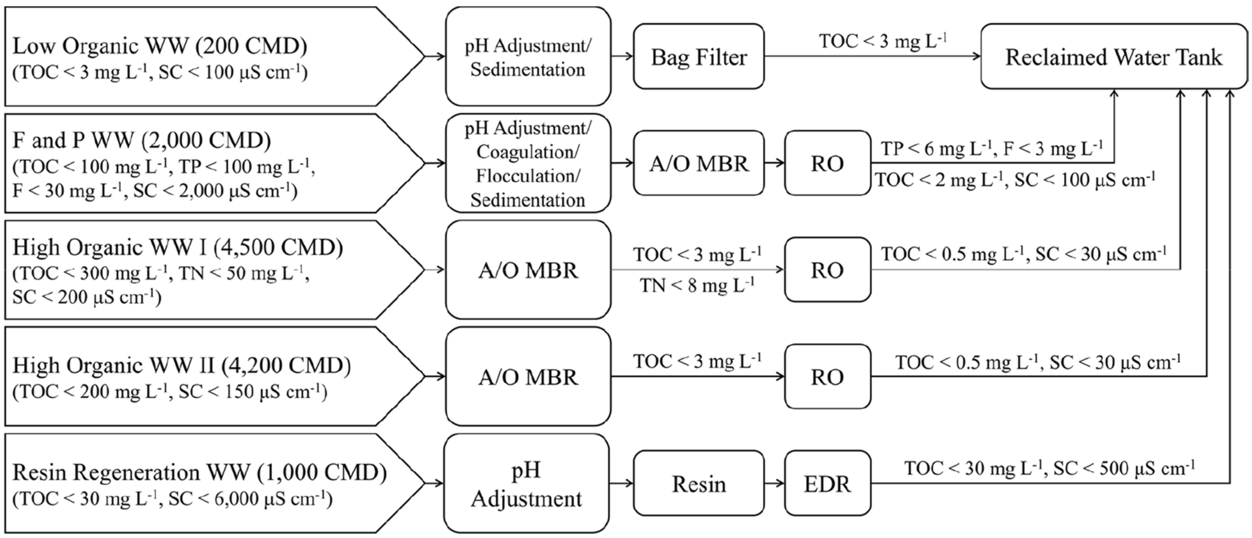

Fig. 5 Reclaimed water from different manufacturing processes in AUO

manufacturing processes. The manufacturing processes at ASE's Nanzih Technology Industrial Park in Kaohsiung are depicted in Fig. 6, which shows the water balance diagram [40].

In regard to water resource recycling and reusing, ASE has established a water reclamation plant to process combined treated wastewater effluent in compliance with local regulatory effluent discharge standards. After treatment process, the reclaimed water is circulated back to the ASE manufacturing facilities for reuse. This has led to a remarkable reduction of approximately 72% in discharged effluent, and it has alleviated the water demand pressure and effluent discharge. Figure 7 illustrates the water balance diagram for the ASE water reclamation plant located in the Nanzih Technology Industrial Park in Kaohsiung. The overall operation and maintenance costs for the ASE reclaimed water is 31.2 NT dollars m^{-3}, including 13.2 NT dollars m^{-3} for treating wastewater collected from manufacturing processes before sending it to the reclamation plant, and 18 NT dollars m^{-3} for reclamation units [40]. The ASE reclaimed water not only secures water supply for manufacturing processes, especially during water shortage situation, but also reduces the cost of purified water for manufacturing processes by 6.6 NT dollars m^{-3}.

Efficient operation and maintenance of water reclamation systems are critical for reducing operation costs and improving reclaimed water quality. The ASE water reclamation plant in Kaohsiung is currently the largest one in Taiwan and in Southeast Asia, with a capacity of 30,000 CMD. It is responsible for treating industrial wastewater effluents collected from different factories in the Nanzih Technology Industrial Park. Wastewater effluents discharged from various factories are collected into a pH adjustment tank for complete

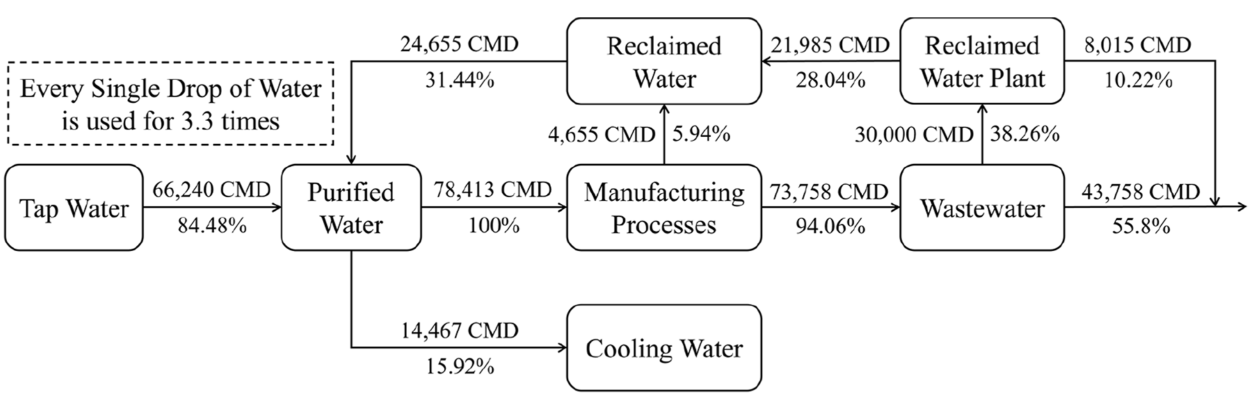

Fig. 6 The water balance diagram for the ASE manufacturing processes in the Nanzih Technology Industrial Park in Kaohsiung

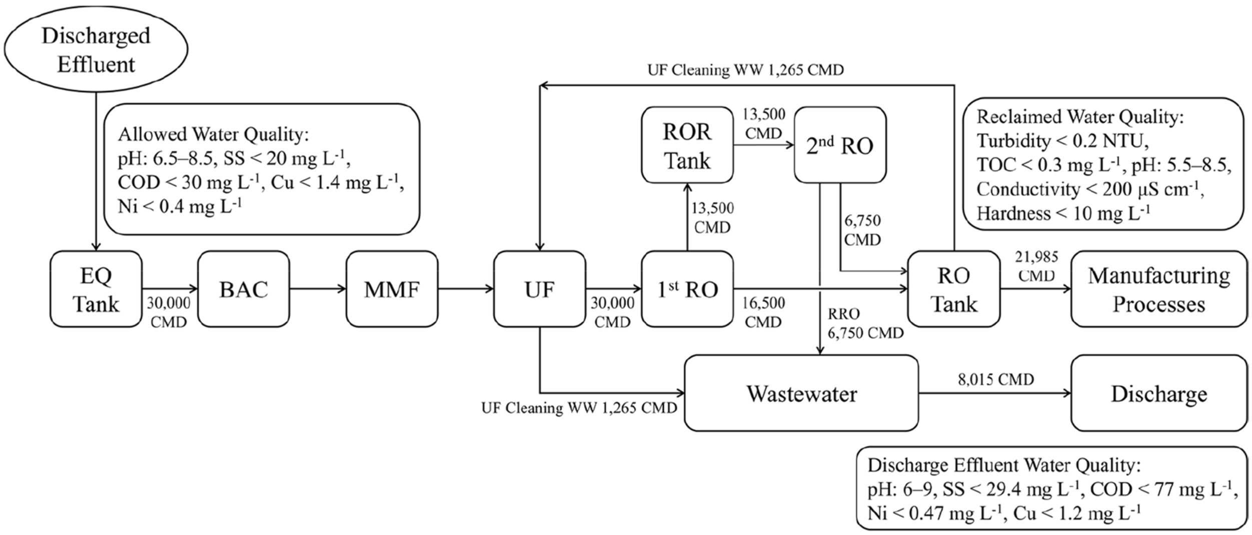

Fig. 7 The water balance diagram for the ASE water reclamation plant in the Nanzih Technology Industrial Park in Kaohsiung

neutralization. After the pH adjustment tank, the reclaimed water undergoes a series of treatment processes, including bio-activated carbon (BAC) filtration, MMF, UF and RO. The influent water of the reclaimed water plant primarily consists of effluents from seven factories, along with a minor quantity of domestic sewage. Due to the complex nature of the water source, operational challenges may arise, leading to incomplete rejection of organic matter, as reported on some occasions. To ensure a high-quality product water, it is crucial to remove compounds from feedwater. ASE utilizes two high-end technologies, fluorescence excitation-emission matrix (FEEM) and high performance size exclusion chromatography (HPSEC), to examine the feedwater characteristics and assess the performance of all units to ensure optimal operating conditions. Both FEEM and HPSEC results aid in determining the efficacy of microorganisms in the BAC in utilizing small organic molecules, thus ensuring the proper function of BAC. Figure 8 shows the HPSEC results for each processing unit. The impact of BAC treatment on the signal intensity and peak pattern of larger molecules was distinct from that of the pH adjustment tank. The data showed that there was a

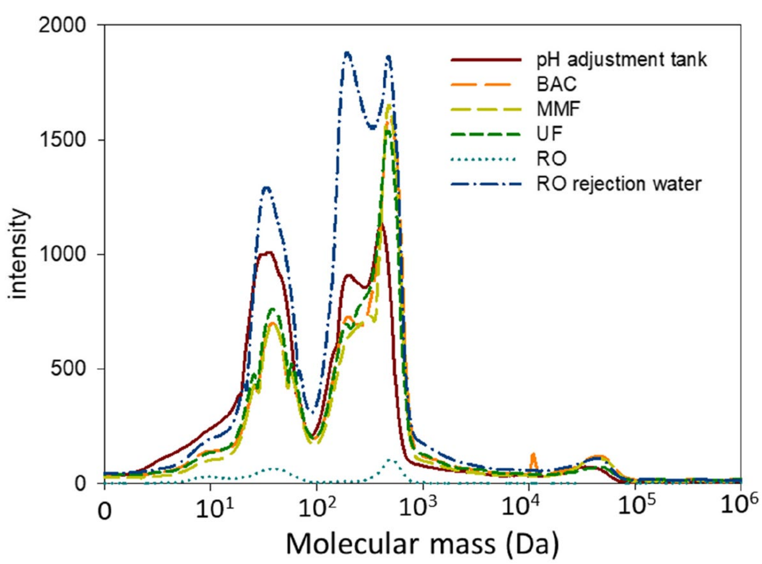

Fig. 8 HPSEC chromatogram of each unit (Signal intensity is monitored by an organic carbon detector)

slight shift to the right in the curve from the pH adjustment tank to the BAC unit, accompanied by a decrease in signal intensity in the small molecule region. The inference drawn is that the smaller molecules were consumed and subsequently converted into larger ones. The similarity in signal patterns observed between MMF, UF, and BAC suggests that these units did not perform significant removal efficiencies. Although the pore size of the UF membrane in this plant can exclude particles larger than 80 kDa, the prevalent molecular size in both BAC and MMF effluents was approximately 1 kDa, rendering it unlikely to have a significant impact on particle removal. In contrast, the RO water displayed a low response, indicating that the RO unit performed effectively and removed the majority of organic materials.

Effective reduction of incomplete rejection of organic matter in RO water requires a careful screening of influent water quality. When abnormal RO water was analyzed via full fluorescence scanning, characteristic breakthrough substances were identified through six pairs of fluorescence excitation wavelength/emission wavelength signals: 254/400, 280/400, 280/308, 280/570, 208/301, and 260/345. These fluorescence signals are utilized as benchmarks for evaluating the quality of the feedwater. Water sources exhibiting high breakthrough signals are excluded from the recovery system, thus reducing the potential for unqualified RO water and minimizing the resources required for downstream secondary water treatment.

4.2 Reclaimed water from municipal wastewater treatment plants

4.2.1 Fengshan reclaimed water treatment plant

Located in Taiwan, the Fengshan reclaimed water treatment plant is the first facility of its kind and handles 85,000 CMD of wastewater gathered from the Fengshan and Niaosong Districts. The plant employs preliminary and primary treatment procedures, with subsequent processing of the primary effluent via an A/O biological process to remove COD and nitrogen. Following the secondary clarifier and chlorine disinfection procedures, roughly 58,885 CMD of effluent undergoes additional treatment via rapid sand filtration, UF, and RO. The Fengshan reclaimed water treatment plant generates and delivers approximately 40,436 CMD of reclaimed water to CSC for use in steel-making processes. The total operational and maintenance cost of the Fengshan reclaimed water treatment plant, including sewage treatment before reclamation units, is about 11.5 NT dollars m^{-3} [41].

Figure 9 provides a summary of the average water quality parameters in the reclamation units. Although the reclamation units at the Fengshan reclaimed water treatment plant can achieve the desired reclaimed water quality with a 68.7% overall water recovery rate, there are instances where the reclaimed water quality exceeds the targeted limits. Between 2019 and 2021, the plant encountered several instances of unusually high COD concentrations in the incoming sewage, caused by illegal dumping of waste oil containing Total Petroleum Hydrocarbons (TPH) and agricultural wastes into the sewer system. The unexpected surge of COD levels in the

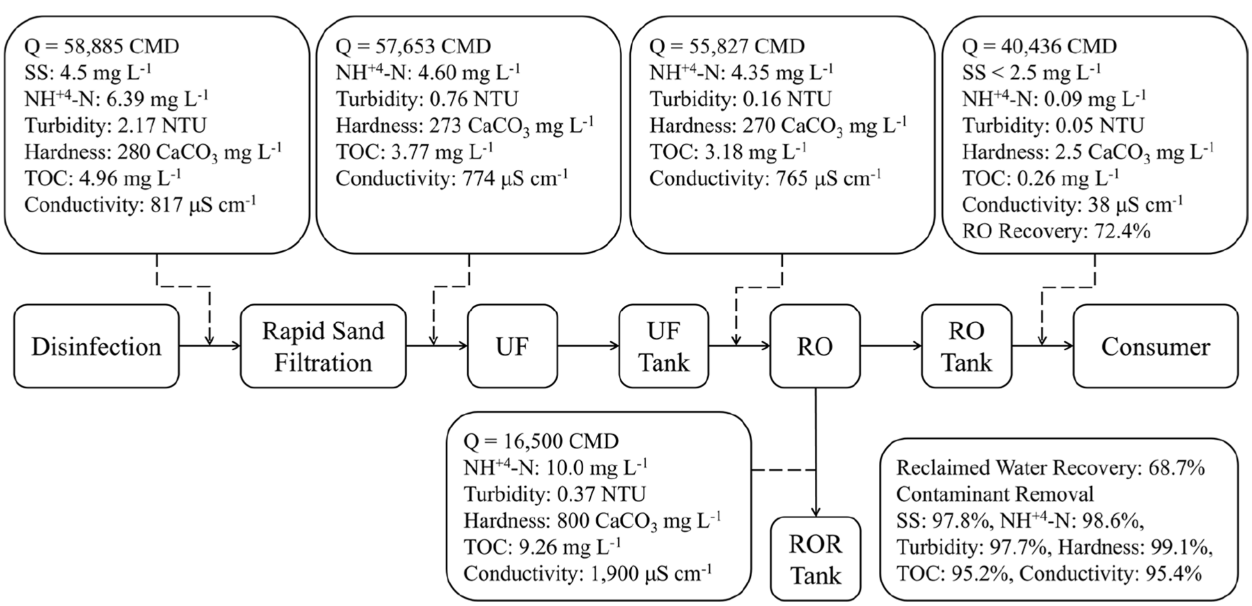

Fig. 9 The averages of water quality parameters in reclamation units of Fengshan reclaimed wastewater treatment plant in Kaohsiung

incoming sewage severely impaired the effectiveness of the A/O biological process, particularly the nitrification process. As a result, the ammonia concentration in the reclaimed water surpassed the targeted limit of 0.5 mg-N L^{-1}.

The ammonia removal efficiency of the A/O system and the primary effluent COD are shown in Fig. 10. The primary effluent COD at Fengshan reclaimed water treatment plant typically does not exceed 300 mg L^{-1} in approximately 90% of cases. However, there were several instances during the periods of 2019/12–2020/02, 2020/05–2020/06, 2020/11–2020/12, and 2021/04–2021/05 where the COD levels exceeded 300 mg L^{-1}. During these periods, the corresponding average ammonia removal efficiencies were notably lower at 12, 39, 50 and 33%, in contrast to the other periods where ammonia removal efficiencies were over 70%. In addition, recovery of stable nitrification performance above 50% took two weeks or longer after inhibition by shock organic loading containing TPH. To meet the targeted reclaimed water quality, the Fengshan reclaimed water treatment plant must maintain stable primary effluent COD below 300 mg L^{-1} and robust biological nitrogen removal by reducing illegal dumping impacts is critical for meeting targeted reclaimed water quality.

4.2.2 Yongkang reclaimed water treatment plant

The Yongkang reclaimed water treatment plant treats 29,000 CMD of sewage from the Yongkang District. It goes through preliminary treatment, primary treatment, and a three-stage A/O MBR process for COD and nitrogen removal. The effluent undergoes an MBR process with a UF unit, followed by RO treatment. This reclaimed water, averaging about 15,500 CMD, is then transported to the Southern Taiwan Science Park for use in semiconductor and TFT-LCD manufacturing processes [42]. The averages of water quality parameters in reclamation units are summarized in Fig. 11.

While the Reclaimed Water Resources Development Act does not regulate urea, the Yongkang reclaimed water treatment plant still needs to remove it to meet the requirements of the Southern Taiwan Science Park water consumer, Taiwan Semiconductor Manufacturing Company (TSMC). The reclaimed water must contain less than 5 ppb of urea before being sent to TSMC. In order to meet the extremely low urea limit, the Yongkang reclaimed water treatment plant has optimized its three-stage A/O MBR process to remove nitrogen, including urea. Methanol is added as a carbon source for denitrification, and the plant is able to maintain urea levels after the RO unit below the required threshold of 5 ppb, with an average of 3.5 ppb. Before reclaimed water is delivered to water consumers in the Southern Taiwan Science Park, an additional step is taken to remove urea through AOP using NaOCl with NaBr as a catalyst. In addition to urea, TSMC also requires boron levels to be below 100 ppb. To meet this requirement, the Yongkang reclaimed water treatment plant optimizes the RO unit to maintain boron levels below 100 ppb, with an average of 70 ppb. The overall operation and maintenance costs for the Yongkang reclaimed water treatment plant amount to 25.8 NT dollars m^{-3}. This includes 8.76 NT dollars m^{-3} for sewage treatment prior to reclamation, 13.14 NT dollars m^{-3} for the RO unit, and 3.94 NT dollars m^{-3} for the removal of urea using NaOCl with NaBr as a catalyst [42].

5 Challenges and future prospects

In the past decade, Taiwan has experienced multiple droughts and water shortages due to climate change. This has resulted in various levels of reduced water supply and restrictions on agricultural, industrial, and domestic water usage. As a result, both the

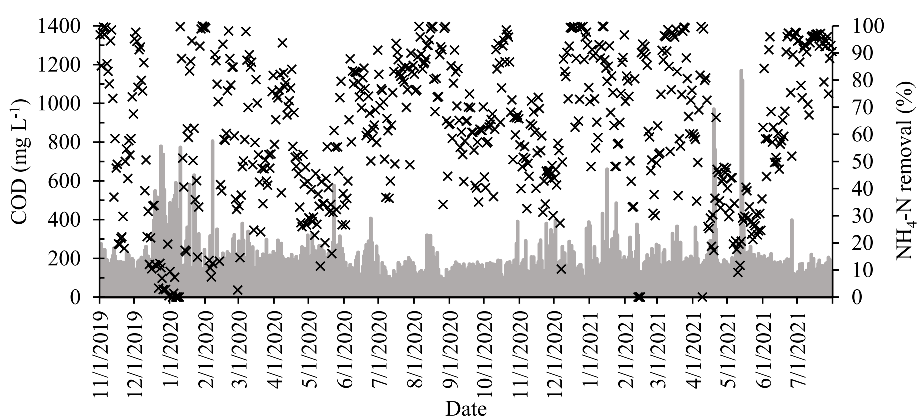

Fig. 10 The ammonia removal efficiency and primary effluent COD in the A/O system of Fengshan reclaimed wastewater treatment plant in Kaohsiung (symbol: ■: COD; ×: NH_4-N removal efficiency)

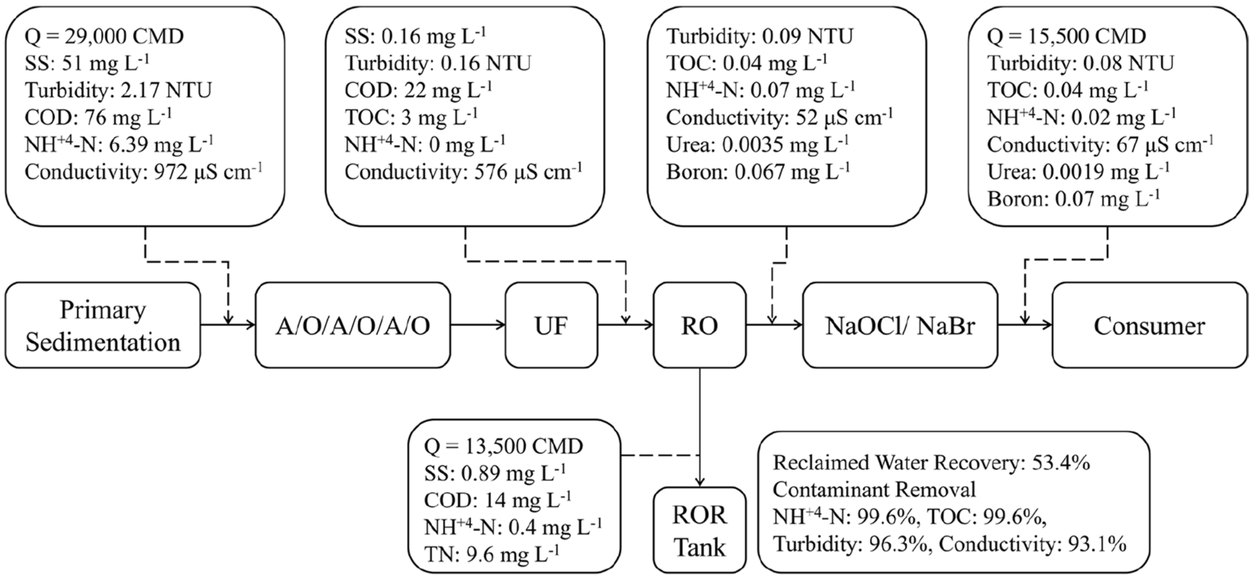

Fig. 11 The averages of water quality parameters in reclamation units of Yongkang reclaimed wastewater treatment plant in Tainan

public and governments have become more concerned about water resource issues. The central and local governments have also started actively seeking new water sources, especially reclaimed water to address this ongoing challenge. Taiwan's goal is to achieve a reclaimed water supply of 1.32 million CMD by 2031, which will include 0.77 million CMD from municipal wastewater treatment plants, 0.45 million CMD from high water-consuming industries, and 0.1 million CMD from industrial park wastewater treatment plants and domestic water consumers. To achieve this goal, the government is actively promoting the use of reclaimed water and identifying potential sources and users. However, despite these efforts, there are still challenges and future prospects that need to be addressed.

5.1 Not mandatory to use reclaimed water

In Taiwan, reclaimed water is primarily utilized by industrial water consumers located in industrial or science parks. Under the Reclaimed Water Resources Development Act, new industrial water consumers are required to use certain percentage of reclaimed water, which varies depending on the severity of water undersupply in their location, but this requirement does not apply to existing industrial water consumers. To further promote the use of reclaimed water, it is crucial to improve current practices by including the amount of reclaimed water used in the environmental impact assessment commitments and gradually increasing the mandatory use of reclaimed water.

5.2 Reclaimed water is more expensive than tap water

The cost of producing reclaimed water includes construction and operation/maintenance expenses. The current price range of reclaimed water from municipal wastewater treatment plants in Taiwan, excluding construction cost, is between 18.8 to 30.9 NT dollars m^{-3}. This is about 56 to 156% higher than the price of tap water for high water-consuming industries. To encourage the use of reclaimed water, it is necessary to narrow the gap between the prices of tap water and reclaimed water by increasing tap water prices for high water-consuming industries and promoting the use of reclaimed water.

5.3 Limitation of potential reclaimed water users

The Reclaimed Water Resources Development Act restricts the use of reclaimed water for drinking water and by the food and pharmaceutical industry, limiting its use to industrial consumers. As to the treated municipal wastewater effluent, it is mainly for miscellaneous water use, such as landscape watering and road cleaning.

It is crucial to find potential users and expand the use of reclaimed water. Currently, agricultural irrigation accounts for roughly 72% of water demand, and during water shortage, agriculture is the first sector to face reduced water supply. Despite this, there is only one official large-scale demonstration site for reclaimed water used in agricultural irrigation due to high water quality standards, particularly in terms of total nitrogen and conductivity as outlined in Table S1 and S3. To increase the use of reclaimed water in agriculture, it is important to address these standards and ensure that they are met, while also promoting the benefits and feasibility of using reclaimed water for irrigation purposes.

5.4 Water quality concerns

Taiwan has identified two primary sources of reclaimed water, namely the wastewater generated by high water-consuming industries and municipal wastewater treatment plants. As indicated in this report, the reclaimed water treatment units are capable of providing high-quality reclaimed water that meets the necessary standards, even for high-tech industrial water usage. However, unexpected contaminant shock loads discharged into the reclaimed water treatment units may pose a significant risk to the quality of reclaimed water. Such loads can cause fouling of the membranes and impair effectiveness. Online monitoring and warning systems, along with measures and back-up plans, are crucial to detecting and mitigating unexpected contaminant shock loads that can negatively impact the quality of reclaimed water and treatment units.

5.5 Establishment of operational parameters and introduction of new technologies for reclaimed water

Although Taiwan has over 20 years of experience with reclaimed water, especially in high-tech industries, detailed operational information is not readily available to the public. With the recent introduction of reclaimed water from municipal wastewater treatment plants, there is a need for long-term operational information. It is crucial to establish systematic information regarding operational parameters, maintenance, energy consumption, and cost to promote effective and sustainable use of reclaimed water. With continuous advancements in sewage treatment and reclaimed water treatment technologies, it is important to integrate and update new technologies with current processes. This is particularly important for highly efficient treatment units with low energy consumption.

5.6 Adjust water supply policy with water exchange program

To achieve cost and energy efficiency for reclaimed water, promoting a "reclaimed water - tap water" exchange program is crucial. Similar to carbon trading, this program is a signed agreement between the reclaimed water provider and the substitute reclaimed water user, establishing contractual obligations and legal responsibilities for water use as stipulated by law. The implementation of a reclaimed water exchange program can help industries use water resources more effectively, particularly during water shortages.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42834-023-00177-8.

Additional file 1: Table S1. Water quality standards for reclaimed water. **Table S2.** Typical effluent water quality of industrial wastewater treatment plants in Taiwan. **Table S3.** Typical effluent water quality of municipal wastewater treatment plants in Taiwan. **Fig. S1.** The average water recovery rate for industrial consumers. **Fig. S2.** RO rejected waterrecycled using EDR and MVR. **Fig. S3.** Mechanical vapor recompression for achieving zero liquid discharge goal.

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Authors' contributions

This study was conceptualized and designed by Liang-Ming Whang and Tsair-Fuh Lin, with information and data collection conducted by a team including Hai-Hsuan Cheng, Wan-Sheng Yu, Shu-Chuang Tseng, Ching-Lin Hsieh, Yi-Ju Wu, Shi-Shuan Lin, Ching-Ping, Chu, Yu-De Huang, Wan-Ru Chen, Tsair-Fuh Lin, and Liang-Ming Whang. The manuscript was written by Hai-Hsuan Cheng, Wan-Sheng Yu, Wan-Ru Chen, and Liang-Ming Whang, and was revised and approved by Liang-Ming Whang. The author(s) read and approved the final manuscript.

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Availability of data and materials

Upon reasonable request, the corresponding author can provide access to the datasets generated during the study.

Declarations

Competing interests

The authors state that there are no apparent financial interests or personal relationships that could have influenced the findings presented in this paper.

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