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Wastewater reclamation trends in Thailand

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ABSTRACT

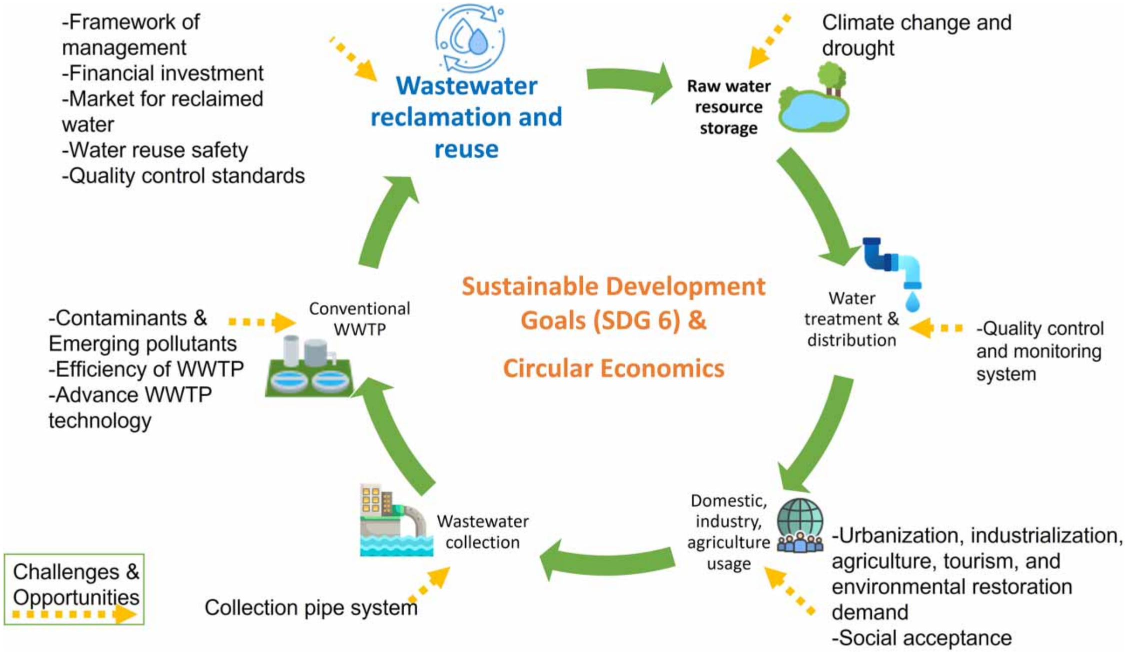
Thailand constantly faces the problem of water scarcity, resulting from an imbalance between available water supply and increasing water demand for economic and community expansion, as well as climate change. To address this shortage, wastewater reclamation is being planned and implemented throughout the country, along with a 20-year, long-term integrated water resource management plan. Significant opportunities from municipal wastewater treatment plants (WWTPs) are dependent on the following factors: the establishment of a reuse water framework and a tangible target for treated wastewater set by local government authorities; widespread recognition and adaptation of wastewater reuse measures in the agriculture, industry, tourism and service sectors regarding climate change and water stress; and the implementation of joint investment water reuse projects between private and government agencies. However, wastewater reclamation faces some significant challenges, specifically: the limitations of regulation and monitoring for specific reuse purposes; a lack of public confidence in the water quality; the limited commercial development of reclaimed wastewater research; and difficulties in self-sustaining business models through adapting circular economy principles. This study aims to provide an overview of the wastewater reclamation, present research trends, currently operating WWTPs as well as opportunities and challenges to speed up water reuse activities in Thailand.

Key words: implementation plans, influential factors, Thailand, wastewater reclamation, wastewater treatment

HIGHLIGHTS

- Thailand's long-term integrated water resource management plan is presented and analyzed.
- There are significant opportunities for wastewater reuse and application.
- Challenges to success of the plan are detailed.

GRAPHICAL ABSTRACT



INTRODUCTION

Water is an important resource for and component of all living things. However, a growing human population is posing major challenges to various water sources by contributing significant pollution through the release of wastewater from households and industrial plants. The determination of wastewater management and reuse policies, including integrated water resource management (IWRM), by scientists and different stakeholders in both the public and private sectors is therefore extremely important, in order to mitigate the pollution of various water resources and at the same time alleviate water shortage problems in both the agricultural and industrial sectors (Rodriguez *et al.* 2020). In 1973, the World Health Organization (WHO) issued for the first time a guideline on how to treat wastewater for reuse with health safeguards. Subsequently, other guidelines followed (WHO 1973), such as for water reuse by the United States Environmental Protection Agency (US EPA) in 1992 (US EPA/USAID 1992), and for treated wastewater for irrigation projects by the International Organization for Standardization (ISO) in 2015 (ISO 2015). Over the past three decades, there has been a shift in the concept of wastewater reclamation and reuse; in particular, it has been included in IWRM plans to supply reliable water resources and alleviate water scarcity in diverse environments (Angelakis *et al.* 2018). Indeed, in 2017 the United Nations World Water Development Report recommended that the vast quantities of wastewater released into the environment could be considered a valuable resource rather than a costly problem (UNESCO 2017). Moreover, the Sustainable Development Goals (SDGs) outlined by the United Nations (UN) provided a new dimension to challenges and opportunities in the water supply and sanitation sector (SDG 6), shifting the paradigm toward a circular economy in which clean water, energy, nutrients and biosolids can be recovered from wastewater (UN 2015). At present, successful initiatives regarding wastewater reuse for agricultural and landscape irrigation and indirect and direct potable uses have expanded in many countries, such as the United States, Japan, Australia, Israel, Cyprus, Spain, Singapore, India, and South Africa (Australian Water Recycling Centre of Excellence; Kellis *et al.* 2013; Khan 2013; Onyango *et al.* 2014; World Bank 2018, 2020).

Global domestic and industrial wastewater production for the year 2015 was approximately 359.4×10^9 m^3 yr^{-1}, and about 80% of the world's wastewater was released to the environment without treatment. In this reference year, wastewater collection and treatment rates were highest in Western Europe (86–88%) and lowest in South Asia (16–31%) and sub-Saharan Africa (16–23%) (UNESCO 2017; Jones *et al.* 2021). The percentages of water that was treated, divided by economic classification (high-, upper-middle-, lower-middle- and low-income countries), were 70, 38, 28 and 8%, respectively (Sato *et al.* 2013). More than 80% of treated wastewater in the Middle East and North Africa (the United Arab Emirates, Kuwait and

Qatar) was utilized; other high figures were seen in small, developed island countries such as the Cayman Islands (78%), the U.S. Virgin Islands (75%) and Malta (67%) (Jones *et al.* 2021). By contrast, considerable untreated wastewater was released to the environment in South and Southeast Asia (wastewater production here was about 25.6×10^9 m^3 yr^{-1}); furthermore, treated wastewater reuse was the lowest here globally, representing just 2% of the wastewater produced (Jones *et al.* 2021).

One country in Southeast Asia, Thailand, generated about 3.5×10^9 m^3 yr^{-1} of municipal wastewater in 2017. It has a total wastewater treatment capacity of about 1.2×10^9 m^3 yr^{-1}, accounting for 34% of the wastewater generated in the country (Pollution Control Department 2017b). Since 2018, Thailand has been planning for wastewater resource management in parallel with the country's 20-year water resource management master plan (2018–2037; 20 yrs-WRM), which conforms to the six strategies launched by the Office of the National Water Resources (Office of the National Water Resources 2019). Strategy 4 of this master plan aims to develop and increase the efficiency of municipal wastewater collection and treatment systems, along with wastewater reclamation. However, the volume of reclaimed water to be achieved by 2037 has been set at 0.132×10^9 m^3 yr^{-1}, accounting for just 3.4% of the wastewater generated in the country (Office of the National Water Resources 2019). Over a recent 30-year period (1989–2017), Thailand experienced drought conditions due to less than average rainfall, which affected people and agricultural areas in many provinces of the country, as shown in Figure 1. In addition, Thailand is presently unable to allocate enough water resources to meet demand in the agricultural and some consumption sectors (Office of the National Water Resources 2019). Such water shortages also affect the economic growth of the community, tourism and industrial sectors, which expect to see greater water demand in the future. To address these shortages, reclaimed water resources are increasingly being used to satisfy water demand. Thus, there is an urgent need for strong plans through the collaboration of the governmental, private and research sectors to promote wastewater reclamation. As a result, reclaimed water can serve as a raw water resource through nationwide water resource management projects. Wastewater reclamation's success also depends on the additional technology used in wastewater treatment facilities to handle emerging pollutants, as necessary to improve the public's perceptions of the quality of reclaimed water (Maryam & Büyükgüngör 2019; Akpan *et al.* 2020).

Although water shortage problems occur in more than 50% of the country's provinces, the high investment costs necessary for advanced wastewater treatment technology that would improve the effluents, along with the significant costs of monitoring the quality and distribution systems of reused water and gaining public acceptance, pose major challenges to the implementation of water reuse projects (Department of Environment Quality Promotion 2013). In 2017, Thailand had 97 active central municipal wastewater treatment plants (WWTPs), covering 55 of the country's 77 provinces (Pollution Control Department 2017b). However, only a small number of treatment systems have installed chlorine disinfection systems beyond secondary treatment, which are suitable for reuse purposes. The additional installation of advanced treatment and pipelines for water reuse is required in most of the provinces.

Future approaches regarding urban development tend to focus on water resource recovery under circular economy principles coupled with economic opportunities to turn wastewater into valuable resources, which may provide financial returns that cover the operation and maintenance costs involved (Rodriguez *et al.* 2020). The current level of wastewater resource recovery in Thailand is not high, despite its potential being considerable.

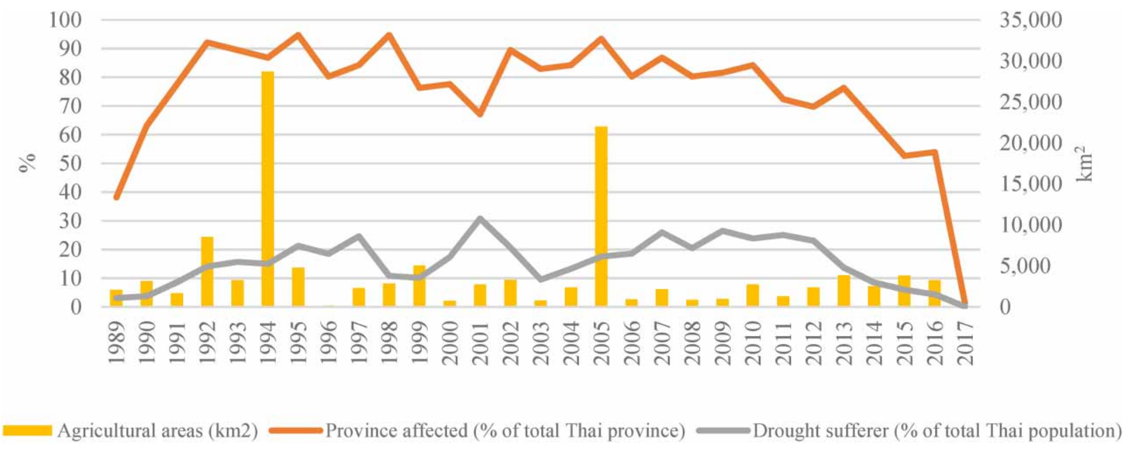


Figure 1 | Proportion of the population and areas affected by drought in Thailand from 1989 to 2017 (Disaster Mitigation Center 2021).

This study reviews wastewater reuse activities in Thailand, the status of available WWTPs, trend of research related with wastewater treatment technologies, and the activities of relevant government and private institutions. It also discusses the opportunities and challenges involved in shifting the paradigm toward smarter wastewater reclamation.

NEEDS OF WASTEWATER RECLAMATION AND REUSE

The Policy and Water Resources Management Committee found that in 2015, Thailand's total water demand was about 152 billion m^3, concentrated in agriculture (75%), industry (3%), consumption and tourism (4%), and ecological conservation (18%) (Water Resources Policy and Management Committee 2015). As shown in Table 1, the amount of annual surface runoff calculated from rainfall, evaporation and infiltration was about 285 billion m^3, while the available surface water that could be retained to serve demand was about 60 billion m^3. Another available water resource, representing about 68 billion m^3, was groundwater, resulting in a total available water supply of approximately 128 billion m^3 with only 103 billion m^3 being achieved for allocation. Thus, it still was not enough to supply the country's water needs in 2015, as mentioned above, especially the allocation of water to the agricultural area outside the irrigation area and some consumer water, about 49 billion m^3. In addition, due to the expansion of the service and tourism sectors as well as local and regional commerce over the next 10 years, the expected water demand of the community, tourism and industrial sectors is likely to increase annually by about 16 billion m^3 on average (Water Resources Policy and Management Committee 2015), leading to further water shortages in the country.

Climate change can cause drought and affect the country's water consumption, and is expected to become more severe in terms of its volatility, frequency and extent in the future. In 2018, according to the data of the Long-Term Climate Risk Index, Thailand was ranked ninth among the world's most vulnerable countries in terms of being affected by long-term climate change, due to both a continuously rising average temperature and the increasing occurrence of disasters thanks to fluctuations in average rainfall from the flood season to the dry season (GERMANWATCH 2018; Office of Natural Resources and Environmental Policy and Planning 2018). Moreover, the Office of Natural Resources and Environmental Policy and Planning (ONEP) has forecasted that over the next 20 years (2018–2037), annual average maximum rainfall in Thailand is likely to increase owing to climate change, albeit distributed over a narrow area, causing 66 provinces' vulnerability to

Table 1 | Water resource supply and demand in Thailand

Source	Value	Unit
Average annual rainfall	1,455	mm/year
Total land area	513,120	km^2
Annual rainfall (1)	748	billion m^3
Evaporation (2)	392	billion m^3
Groundwater infiltration (3)	70	billion m^3
Annual surface runoff = (1)−(2)−(3)	285	billion m^3
Available surface water (4)	60	billion m^3
Accumulated groundwater	1,130	billion m^3
Available groundwater (5)	68	billion m^3
Total available water (6) = (4) + (5)	128	billion m^3
Use purpose of allocated water		
Irrigation (7)	65	billion m^3
Drinking water/daily water (8)	6.5	billion m^3
Industry (9)	4.2	billion m^3
Save the ecosystem (10)	27	billion m^3
Total allocated water (11) = (7) + (8) + (9) + (10)	103	billion m^3
Total water demand (12)	152	billion m^3
Water shortage (3) = (12)−(11)	49	billion m^3

Summarized from (Water Resources Policy & Management Committee 2015; Office of the National Water Resources 2019).

drought to rise. The highest incidence of drought is expected to be in the north, followed by the central, western and northeastern regions (Office of Natural Resources and Environmental Policy and Planning 2018).

Drought has already caused significant damage to the Thai economy. In the UN Economic and Social Commission for Asia and the Pacific (ESCAP)'s 2019 assessment of loss from disaster risk in the Southeast Asia region, Thailand ranked third, with losses due to drought (mainly in the agricultural sector) estimated at US$ 9 billion (UN ESCAP 2020). In addition, domestic statistical data indicate that the damage caused by drought tended to increase by about US$ 220, 530 and 850 million in 2005, 2014 and 2020, respectively, resulting in increased poverty and inequality among farmers, as a large proportion of Thailand's labor force works in the agricultural sector (Office of Natural Resources and Environmental Policy and Planning 2018). Drought also affects the country's ability to meet its income targets according to its 20-year National Strategy Plan, which challenges the country to progress from the upper-middle-income group to the high-income group of countries by 2036 (Office of Natural Resources and Environmental Policy and Planning 2018).

Based on the effects of drought that are already being seen in diverse domains, Thailand has prepared drought management guidelines under the National Climate Change Adaptation Plan 2018–2037. One important measure, which has already led to various activities and research related to wastewater reclamation, is to promote the development and use of wastewater treatment technology to recycle water in households and industry. The overall objective is to reduce the impact of water scarcity conditions, especially in drought areas outside the irrigation boundary, which rely on groundwater supply (UN ESCAP 2020).

THE STATUS OF WASTEWATER RECYCLING IN THAILAND

Thailand is a unitary state and is divided by regional administration into central, provincial and local levels. There are 76 provinces and one special administrative area, representing the capital, Bangkok (National Statistical Office of Thailand 2019). Initially, each local government organization was responsible for managing its wastewater treatment system, creating problems in controlling the quality of the treatment system and providing a sufficient operating and maintenance budget. However, in 2005, to achieve the effective management of wastewater treatment systems, a wastewater management organization under the Ministry of Interior assumed responsibility for the study, design, construction, renovation, operation and maintenance of systems throughout the country, according to a royal decree (Wastewater Management Authority 2018). In 2019, the government and related agencies have formulated a wastewater management plan, along with the 20 yrs-WRM, to increase treatment efficiency and control of wastewater discharge into the environment (Office of the National Water Resources 2019). This plan's strategies regarding wastewater recycling include: 1. Prevention and reduction of wastewater at the source for all households in urban communities, by reducing both the volume and the contamination of wastewater; and 2. Enhance the efficiency of collection and treatment and control the effluent volume discharged to the environment by reusing treated water in the industrial, service and housing sectors. Furthermore, the plan's targets include a total of 842 WWTPs across the country, with 57% of total wastewater being treated to meet the national quality standards, and 0.132 billion m^3/yr of water being reclaimed (Office of the National Water Resources 2019). In 2020, all municipalities were able to collect about 38% of their income to solve their problems, including the cost of WWTPs, and thus relied on income from the central government (Parliamentary Budget Office 2020). The Ministry of Natural Resources and Environment is the central government agency responsible for overseeing and allocating environmental infrastructure budgets to regional and local authorities. The budget for environmental management in Thailand in 2020 was approximately US$ 40 million, or 0.042% of the country's total budget, divided into a water quality and wastewater management budget of US$ 20 million according to the 20 yrs-WRM plan, as mentioned above (Office of the National Water Resources 2019; Pollution Control Department 2021).

Most of Thailand's municipal and industrial wastewater treatment systems are conventional, consisting of chemical treatment (coagulation, flocculation), physical treatment (sedimentation, sand filtration), biological treatment (activated sludge (AS), stabilization pond (SP), constructed wetland (CW)) and chlorine disinfection (Industrial Estate Authority of Thailand; Pollution Control Department 2017b). However, conventional treatments are often ineffective in treating the wide variety of emerging pollutants, such as persistent organic pollutants (POPs), per- and polyfluoroalkyl substances (PFAS), pharmaceutical residues, and antibiotics (Schultz *et al.* 2006; Kunacheva *et al.* 2011; Wang *et al.* 2021). Most treated wastewater meets the national effluent quality criteria for discharge to the public as shown in Table 2, covering six parameters – pH, biological oxygen demand (BOD), suspended solids (SS), oil and grease (O&G), total nitrogen (TN), and total phosphorus (TP) (Ministry of Natural Resources and Environment 2010). However, this wastewater is not suitable for reuse in human or food contact applications because new groups of emerging pollutants that may affect human health and the environment are not included.

Table 2 | Type of wastewater treatment system and quality control standard in Thailand

Domestic wastewater system			Law and regulation				
			Act		Quality control standard		
Type	Scope	Systems	Issue	Name	First issue	Name (No. of Parameters)	Parameter list
On-site	Individual household and buildings	O&G trap, cesspool, septic tank, commercial package system	1979	Building Control Act	1994	1. Building effluent std. (8) (Ministry of Natural Resources and Environment 1994)	-pH, BOD, SS, Fat O&G (common) -TDS, settable solids, TKN, sulfide (only topics 1 and 2)
	Real estate, housing estate	On-site WWTP	1992	NEQA	1996	2. Real estate effluent std. (8) (Ministry of Natural Resources and Environment 2021)	-TN, TP (only topic 3)
Cluster	Small community	Combined sewer, pumping station and small WWTP (50–500 m^3/day)	1992	NEQA	2010	3. Central WWTP effluent std. (6) (Ministry of Natural Resources and Environment 2010)	
Central	Large community	Combined sewer, pumping station and central WWTP					
Industrial wastewater system							
On-site	Individual factory	On-site WWTP	1979	Industrial Estate Authority Act	1987	4. Effluent control std. into central WWTP for factory (30) (Industrial Estate Authority of Thailand 2017)	-pH, BOD, COD, SS, TDS, TKN, O&G, temperature, color, odor, Hg, Se, Cd, Pb, As, Cr^{+3}, Cr^{+6}, Ba, Ni, Cu, Zn, Mn, H_2S, HCN, formaldehyde, phenols, free chlorine, pesticides (common)
			1992	Factory ACT	1996	5. Effluent control std. for factory (28) (Ministry of Industry 2017)	
Central	Industrial estate	Separated sewer, pumping station and WWTP	1992	NEQA	1996	6. Factory, industrial estate and industrial zone effluent control std. (28) (Ministry of Natural Resources and Environment 2016)	-Surfactants (only topic 4)

NEQA, Enhancement and Conservation of National Environmental Quality Act; SS, suspended solids; TDS, total dissolved solids; TP, total phosphorus; TN, total nitrogen; TKN, total Kjeldahl nitrogen; HCN, hydrogen cyanide; Std., standard.

Existing regulations and standards relating to the recycling of wastewater from central municipal WWTPs in Thailand for specific uses are obscure, and instead often refer to surface water quality standards for agricultural purposes (National Environment Board 1994). In addition, there are voluntary water quality criteria for water recycling in agricultural areas established by the Department of Environmental Quality Promotion (DEQP) in 2013 (Department of Environment Quality Promotion 2013). The Pollution Control Department issued guidelines regarding community water management in 2016 along with general recommendations concerning the disinfection of treated wastewater before it is recycled in households for non-human contact uses, such as watering plants and lawns and washing floors (Pollution Control Department 2016). The criteria for the reuse of treated water from the WWTPs in industrial estates or individual factories are also not well regulated. There is only the quality control standard for wastewater discharged from factories and industrial estates into the environment as shown in Table 2 (Industrial Estate Authority of Thailand 2011; Ministry of Industry 2017). However, in 2020 the Ministry of Industry announced for the first time the temporary use of effluents from WWTPs in agricultural areas during droughts, by requiring that the quality of treated wastewater for reuse must meet the industrial effluent standards, and limiting the amount of reuse to 6.25 L/m^2/day (Ministry of Industry 2017). Moreover, in 2021 the Department of Industrial Works announced general guidelines for the efficient reuse of treated wastewater in drought situations. It is recommended to treat the effluents from the cooling tower or final wastewater treatment pond using an ultrafiltration/reverse osmosis

(UF/RO) system before reuse in the cooling system or production support equipment (Department of Industrial Works 2021). However, there is still no regulation controlling the quality of treated wastewater for specific purposes within factories.

From the above, it can be seen that Thailand does not have clear criteria regarding the quality of reclaimed water for specific purposes. As a result, international standards are suggested as a reference instead, such as ISO 20761 ('Guidelines for water reuse safety evaluation,' 2012) (ISO 2018b), U.S. EPA ('guidelines for water reuse,' 2012) (U.S. EPA 2012), WHO ('guidelines for the safe use of wastewater (excreta and greywater),' 2006) (WHO 2006), 'Australian guidelines for water recycling,' 2006 (*Australian guidelines for water recycling: managing health and environmental risks (Phase 1) 2006*), and technical guideline standards for treated wastewater reuse in Japan enacted in 2005 (Takeuchi & Tanaka 2020). When setting quality criteria for the reuse of treated wastewater, it is important to be aware of health and environmental safety, to prevent damage to the assets of the distribution, storage and end uses, and to ensure public acceptance (ISO 2018b). Table 3 compares the quality control parameters of treated wastewater from Thai WWTPs (as shown in Table 2) with the relevant reuse water safety parameters described in ISO 20761. Table 3 implies that when upgrading or installing WWTPs with regard to wastewater reclamation, more quality control parameters should be analyzed to assess the risk to health, environmental and facilities safety, especially microbial and stability parameters, which have yet to be measured by any effluent standard.

Municipal wastewater treatment systems in Thailand can be classified into three types as follows: 1. On-site wastewater system; 2. Cluster wastewater system; and 3. Central wastewater system, as shown in Table 2. The Pollution Control Department has issued guidelines for the management of wastewater from houses and buildings (e.g., hotels, hospitals, schools, offices, department stores, restaurants, markets) since 2017. Individual point sources should install primary wastewater treatment with grease traps and septic tanks, followed by a small wastewater treatment system (an on-site wastewater system) to improve the quality of wastewater to meet the building effluent standard (Ministry of Natural Resources and Environment 1994), before discharging to public sewers or seepage ponds. In addition, to collect wastewater from individual point sources for further treatment, a cluster wastewater system (a small WWTP with a wastewater volume of 50–500 m^3/day) is used for small communities. In 2017, approximately 38 of these systems existed, generally with simple biological wastewater treatment systems such as vertical CW, septic tank, hybrid oxidation pond, anaerobic filtration, sand filter, trickling filter or contact aerated filter (Pollution Control Department 2017a).

In the 1990s, most of the central WWTPs in Thailand were SP and AS, with nitrogen and phosphorus removal introduced to the WWTPs in Bangkok from 2000 (JICA; TEC and NK company 2011). These pipe collection systems are combined sewer pipe systems. The central WWTPs usually comprise two steps: primary treatment and secondary treatment. Primary treatment consists of coarse and fine sieves, a sand trap, a grease trap and a preliminary sedimentation tank to separate large solids, while secondary treatment consists of a biological reactor to remove suspended solids and organic matter from

Table 3 | Relevant reuse water safety parameters and their differences from the Thai effluent quality control standards

Types	Reuse water quality control parameters (ISO 2018b)	Different parameters compared with effluent std.	
		Domestic WWTP	Industrial WWTP
Routine physical and chemical parameters	pH, BOD_5, COD, TOC, N, P, DO, TDS, TSS, turbidity, ammonia, alkalinity, hardness, chlorine demand, residual chlorine	COD, TOC, DO, turbidity, ammonia, alkalinity, hardness, chlorine demand, residual chlorine	TOC, P, DO, turbidity, ammonia, alkalinity, hardness, residual chlorine
Aesthetic parameters	Color, odor	Color, odor	
Microbial parameters	Indicator bacteria (coliforms, *E. coli*, etc.) Environmental pathogens	Indicator bacteria (e.g., coliforms, *E. coli*)	
Stability parameters	-Chemical stability: specific ions (e.g., Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}) -Biological stability: heterotrophic plate counts (HPC), algae, etc	Both chemical and biological stability	
Toxic and harmful chemicals	-Specific metal (e.g., Pb, Hg, Cd) -Oil and grease -Surfactants	Surfactants	

BOD_5, biochemical oxygen demand; COD, chemical oxygen demand; TOC, total organic carbon; DO, dissolved oxygen; TDS, total dissolved solids.

wastewater. In 2017, there were 101 constructed sites of central WWTPs, comprising 12% with a capacity exceeding 50,000 m^3/day (large systems), 45% with a capacity of 10,000–50,000 m^3/day (medium-sized systems), and the rest with a capacity below 10,000 m^3/day (small systems). Table 4 presents the details of 97 completed and operational central WWTPs (out of a total of 101 construction projects) and 7 cluster wastewater systems spread across the country (Office of the Environment Region 1-16 2016; Pollution Control Department 2017b; Office of Strategy and Evaluation 2020). The total treatment capacity of WWTPs is only 2.64 mil.m^3/day, accounting for 26.6% of the total wastewater volume of 9.93 mil.m^3/day (Pollution Control Department 2021). The most frequently installed type of WWTP is a stabilization pond (SP), accounting for 42%, followed by oxidation ditch (OD) (21%), aerated lagoon (AL) (18%) and AS (16%), including sequencing batch reactor (SBR) and membrane sequencing batch reactor (MSBR). Some treatment plants use more than one type, such as CW + SP and AS + SP.

Bangkok is the capital city of Thailand and one of the most densely populated areas in the world. It has operated municipal wastewater treatment projects since 1994 (JICA; TEC and NK company 2011). By 2020, Bangkok had 8 large and 12 small WWTPs, with a total wastewater treatment capacity of 1,136,800 m^3/day. The large treatment system is AS with phosphorus (P) and nitrogen (N) removal, while the smaller treatment systems distributed in community areas are AL, AS and SP without nutrient removal. A large sewerage system covers a population of approximately 3.5 million people. However, treated municipal wastewater accounts for 43.7% of the city's water consumption and the service area covers approximately 213 km^2 or 13.5% of the urban area. It has been recognized that there is still a need to expand the wastewater collection and treatment systems to cover the rest of the city (Strategic and Evaluation Office 2020). The Drainage and Sewerage Department of Bangkok is responsible for managing both the drainage system and the collection of wastewater from the sources for treatment in the central WWTP, including monitoring, inspecting and controlling the quality of treated wastewater and water sources (Drainage and Sewerage Department BMA).

Initially, not all municipal wastewater treatment systems in Thailand were designed for water reuse. At present, advanced wastewater treatments such as membrane bioreactor (MBR) and reverse osmosis (RO) have not been widely applied to central WWTPs. For example, in 2016 a project in Phuket municipality (a famous tourist attraction in Thailand) aimed to take treated wastewater from conventional WWTPs back into the RO treatment system and reuse for community consumption, instead of releasing into the sea (Office of the Environment Region 15 2021). Some RO applications have been found in WWTPs for leachate at waste-to-energy power plants and waste transfer stations (Department of Alternative Energy Development and Efficiency 2014). In addition, some municipal WWTPs have installed sand filters and chlorine disinfection units as final treatment units. The treated wastewater disinfected with chlorine will be recycled for many purposes, for instance in green spaces and agricultural irrigation, livestock uses, seedling cultivation, cleaning public water pipes, cleaning roads, and washing garbage trucks, as shown in Figure 2.

WWTPs on industrial estates are another potential source of water reuse. As of 2021, Thailand has 62 industrial estates, spread across 18 provinces. The Industrial Estate Authority of Thailand (IEAT) is responsible for the central WWTP of each industrial estate. The wastewater of each factory must be preliminarily treated by the owner until meeting the water quality criteria specified by the IEAT, before being collected and treated again in the central WWTP of the industrial estate (Industrial Estate Authority of Thailand 2017). At present, there are in total 60 sites of WWTP of the industrial estates surveyed within this research, most of which (73%) are AS/SBR systems, while the rest are SP, AL and rotating biological contactor (RBC), as shown in Table 3. Recently, advanced treatments such as AC, microfiltration (MF), UF and RO have been used to improve effluent quality in addition to the biological WWTPs of eight industrial estates in Chonburi, Rayong, Prachinburi, Ang Thong and Samut Sakhon provinces. This treated water is often used as raw water for industrial water production, and as cooling water for industrial processes and electrical power plants (Office of Natural Resources & Environmental Policy and Planning 2021).

A sustainable increase in wastewater reuse is necessary to solve problems related to the operation and maintenance of WWTPs, in order to effectively and continuously maintain effluent quality. The problems encountered in both collection and treatment systems, summarized based on the survey and evaluation reports of municipal WWTPs at the provincial level from 2013 to 2017 (Office of the Environment Region 1-16 2016; Pollution Control Department 2017b; Office of Strategy and Evaluation 2020), are presented in Table 5. Common problems in wastewater treatment systems include blockages and breakdowns of the sewage collection pipe system. As a result, the amount of wastewater entering the treatment system may be lower than the designed value. Some WWTPs had less than 20% of the intended water intake (see Table 4), leading to effluent quality that was not suitable for reuse.

Table 4 | Number and treatment capacity of municipal and industrial estate WWTPs in Thailand, along with wastewater reuse activity

			Municipal WWTP					**Industrial estate WWTP**				
Region	**Province name and no. of municipalities[e]**	**River basin**	**Type**	**No.**	**Treatment capacity (m^3/day)**	**Actual treatment (%)**	**Treated wastewater reuse activity**	**Type**	**No.**	**Treatment capacity (m^3/day)**	**Actual treatment (%)**	**Treated wastewater reuse activity**
North	Chiang Mai (5)	Ping	AL + Sed.P + OD	1	55,000	18	A					
	Chiang Rai (1)	North Khong	AL + Sed.P + Chlor.P	1	27,200	37						
	Kamphaeng Phet (3)	Yom	SP + Chlor.P	2	14,000	23						
	Lampang (4)	Yom	SP + CW	1	12,300	33	A, E					
	Lamphun (1)	Ping	AS(SBR) +UV	1	10,000	100	G1	SP + AL	1	24,000	61	G1, C2, C4, CT
								AS	1	2,000	106	
	Nakhon Sawan (3)	Chao Phraya	SP	1	1,650	51	G1					
			AS (MSBR) + Chlor.P	1	36,000	100	G1					
	Nan (1)	Nan	SP + Chlor.P	1	8,259	67						
	Phayao (2)	Yom	SP	1	9,700	49	A					
	Phichit (3)	Nan	AL + Maturation Pond	1	12,000	42		SP	1	5,100	4	G1
			SP	1	7,164	14						
	Phitsanulok (2)	Nan	SP	1	25,000							
			Septic and Aeration[f] Filter Tank	2	320							
	Sukhothai (3)	Yom	SP	1	8,400	83	A					
	Tak (2)	Ping, Salawin	SP + Chlor.P	2	16,400	37						
Northeast	Amnat Charoen (1)	Mun	SP	1	12,819	46	A, G2					
	Buriram (3)	Mun	AL + Chlor.P	1	13,000	62	A, G2					
	Chaiyaphum (1)	Mun	AL	1	5,000							
	Kalasin (2)	Chi	AL + Chlor.P	1	14,000	3	A					
	Khon Kaen (7)	Chi	AL + Chlor.P	1	78,000	51	G1, S, C1, C2					
			CW[f]	1	400	63	G1					
	Maha Sarakham (1)	Chi	SP + Chlor.P	1	4,200	81	G1					
			SP + CW	1	1,500	50						
	Mukdahan (1)	Northeast Khong	SP	1	8,500	36	A, G2					
	Nakhon Ratchasima (5)	Mun	SP + AS	1	70,000	71			1	4,000	56	G1, C2, C4, P1
			SP	2	15,000	56	G1					
	Sakon Nakhon (1)	Northeast Khong	SP + wetland	2	18,054	72						

(*Continued.*)

Table 4 | Continued

			Municipal WWTP					Industrial estate WWTP				
Region	Province name and no. of municipalities[e]	River basin	Type	No.	Treatment capacity (m^3/day)	Actual treatment (%)	Treated wastewater reuse activity	Type	No.	Treatment capacity (m^3/day)	Actual treatment (%)	Treated wastewater reuse activity
	Surin (1)	Mun	SP	1	13,600	81	A, L					
			CW	1	360	56						
	Ubon Ratchathani (5)	Mun	AL	1	22,000							
			SP	1	18,000	17	A, F					
	Udon Thani (4)	Northeast Khong	SP + Chlor.P	1	43,902	34		AS	1	6,400	87	G1 (buffer zone), C2, C4
	Yasothon (1)	Chi	SP	1	7,246	38	A, F					
East	Chachoengsao (1)	Bang Pakong	OD + Chlor.P	1	12,000	58		AS	3	20,600		G1, CT
			SP + CW + Chlor.P	1	5,000	40		AL	1	7,200		
								SBR	1	8,400		
	Chanthaburi (5)	East Coast Gulf	SP	2	21,500	35						
	Chonburi (12)	Bang Pakong, East Coast Gulf	OD	3	41,000	66	G1, C3	AS, AS + AL	8	55,650		G1, C2, C4, P2, P3 (UF + RO (3 plants))
			SP	1	5,380	44		AL, SP + AL	5	29,950		
			AS (SBR) + Chlor.P	3	110,500	95		SBR	2	85,000		
			AL	2	12,900	35						
	Prachinburi (1)	Bang Pakong						Anaerobic pond + AL	1	4,500		G1, C2, C4, P3 (UF (1 plant))
								AS-SBR	1	5,280		
	Rayong (3)	East Coast Gulf	AL + Chlor.P	2	16,000	9		AS	5	77,820		G1, C2, C4, P2, P3 (UF + RO (1 plant) and MF (1 plant))
			OD + Chlor.P	1	8,000	11.5		SBR, SBR + CW, SBR + BAF	3	63,200		
			AS[f]	2	1,300	91		AL	4	41,000		
	Sa Kaeo (3)							Biological treatment	1	2,100		
South	Krabi (1)	Peninsula-W/E[a]	AS + CW	1	400	150						
			AL	1	12,000	51	A					
	Nakhon Si Thammarat (4)	Peninsula-U/E[b]	SP	1	33,000	30						
		Peninsula-W/E[a]	RBC	1	10,000	50	G1, C3					
	Phuket (3)	Peninsula-W/E[a]	OD + Chlor.P	3	65,350	78	Tap water by RO					

(*Continued.*)

Table 4 | Continued

Region	Province name and no. of municipalities[e]	River basin	Municipal WWTP Type	No.	Treatment capacity (m^3/day)	Actual treatment (%)	Treated wastewater reuse activity	Industrial estate WWTP Type	No.	Treatment capacity (m^3/day)	Actual treatment (%)	Treated wastewater reuse activity
			AS + Chlor.P	3	10,560							
	Songkhla (13)	Thale Sap Songkla	SP + CW	1	138,000	27	G1	AS	3	18,700		G1, C2, C4
			AL + Chlor.P	1	35,000	71	A					
	Surat Thani (5)	Peninsula-U/E[b]	CW	1	200	30						
			OD	3	17,050							
	Trang (2)	Peninsula-W/E[a]	AL	1	17,700	57						
	Yala (3)	Peninsula-L/E[c]	SP	1	3,200							
			AL	1	4,600							
Center	Ang Thong (1)	Chao Phraya	AL	1	8,200	31	A	AS	1	6,610		G1, C2, C4, P3 (UF + RO (1 plant)
	Ayutthaya (6)	Chao Phraya	OD + AL	1	24,000	42	A (rice field)	AS	3	42,800		G1, C2, C4
	Bangkok (capital)	Chao Phraya	AS	8	1,112,000			AS	2	22,300		
	Chai Nat (1)	Tha Chin	AL + SP	1	5,870	61	A (rice field)					
	Kanchanaburi (3)	Mae Klong	OD	1	24,000							
	Lopburi (3)	Pasak	SP + Chlor.P	1	1,000							
	Nakhon Pathom (6)	Tha Chin	SP	1	25,000	33						
	Nonthaburi (9)	Chao Phraya	OD + Chlor.P	1	38,500	34						
	Pathum Thani (10)	Chao Phraya	AL	1	11,000	11						
	Phetchaburi (2)	Phetcha-Prachuap[d]	SP	1	10,000	47	E (mangrove forest)					
			AL	1	17,000	29	G1					
	Prachuap Khiri Khan (2)	Phetcha-Prachuap[d]	AL + SP	1	8,000	79						
			RBC + Chlor.P	1	8,000	100	G3					
			OD + Chlor.P	1	17,000	71						
	Ratchaburi (4)	Mae Klong	SP	2	25,000	47	A (rice, lotus), L	AS	1	32,000		G1, C2, C4, CT
			OD + Chlor.P	1	5,000	64						
	Saraburi (4)	Pasak	OD	1	24,000			AS	2	13,200		
	Sing Buri (2)	Chao Phraya	SP	1	4,500	33						
	Suphan Buri (2)	Tha Chin	SP	1	12,500	74						
	Samut Prakarn (7)	Chao Phraya						AS	4	69,400	62	

(*Continued.*)

Table 4 | Continued

Region	Province name and no. of municipalities[e]	River basin	Municipal WWTP Type	No.	Treatment capacity (m^3/day)	Actual treatment (%)	Treated wastewater reuse activity	Industrial estate WWTP Type	No.	Treatment capacity (m^3/day)	Actual treatment (%)	Treated wastewater reuse activity
								RBC	1	2,300		
	Samut Sakorn (4)	Tha Chin	AS prefabricated[f] Tank	2	160	100		AS	2	24,000		G1, C2, C4, P3 (AC + UF (1 plants))
								UASB + SBR	1	1,500		

AC, Activated carbon; AL, Aerated lagoon; AS, Activated sludge; BAF, Biological aerated filtration; Chlor.P, Chlorine contact pond; CW, Constructed wetland; MSBR, Membrane sequencing batch reactor; OD, Oxidation ditch; RBC, Rotating biological contactor; SBR, Sequencing batch reactor; Sed.P, Sedimentation pond; SP, Stabilization pond.

A, Agricultural irrigation; C1, Cleaning public water pipes; C2, Cleaning roads; C3, Washing garbage trucks; C4, Cleaning equipment; CT, Factory construction; E, Ecological preservation; F, Fishery; G1, Green space irrigation; G2, Gardening irrigation; G3, Watering golf courses; L, Livestock uses; P1, Second-grade water for factories; P2, Cooling water for factories; P3, Raw water for industrial water production; S, Seedling cultivation.

[a]Peninsula-West/East Coast.

[b]Peninsula-Upper East Coast.

[c]Peninsula-Lower East Coast.

[d]Phetchaburi-Prachuap Khiri Khan.

[e]Population density > 3,000 people/km^2 (Department of Local Administration 2020).

[f]Cluster wastewater system.

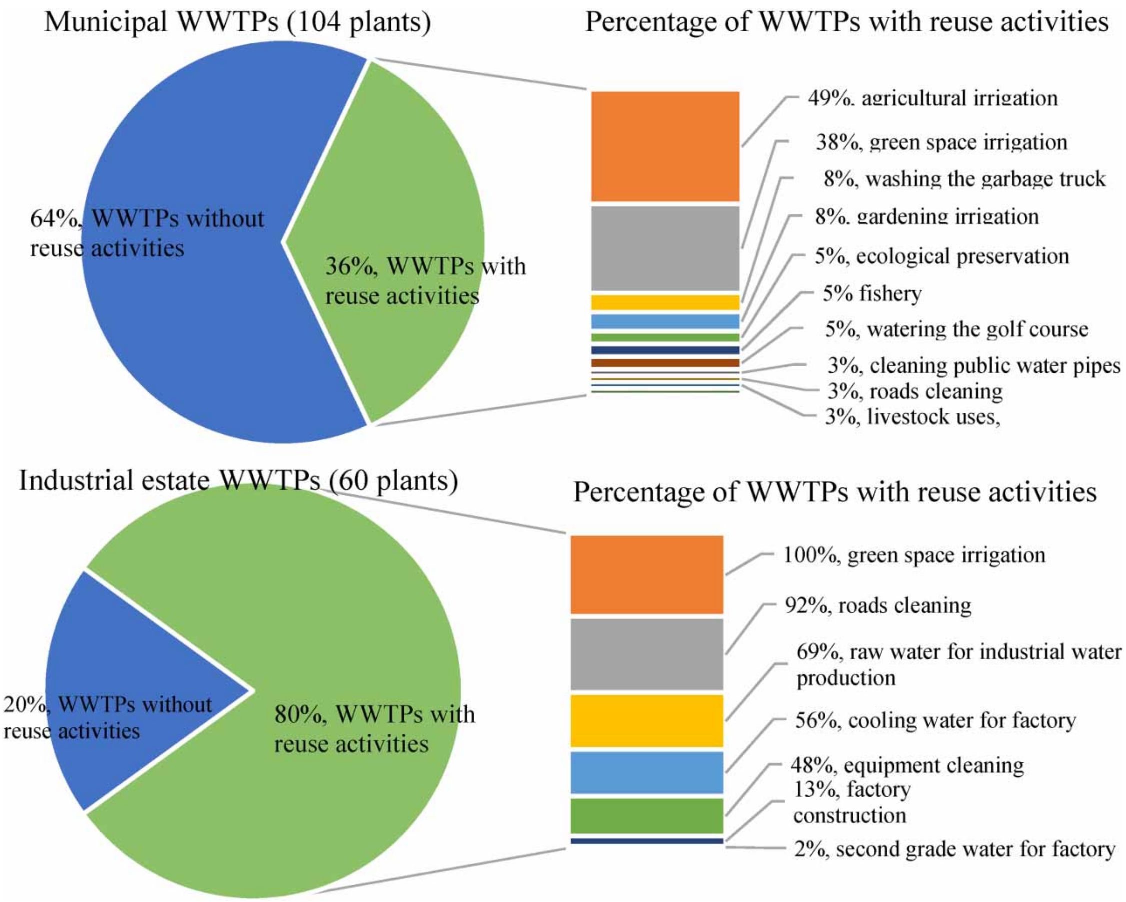


Figure 2 | Utilization of treated wastewater from municipal and industrial estate WWTPs in Thailand.

CURRENT RESEARCH TRENDS RELATED TO WASTEWATER TREATMENT FOR REUSE IN THAILAND

At present, most of the WWTPs in Thailand are conventional treatment plants. With greater environmental awareness among the community, more advanced treatment methods are required to meet the increased effluent quality criteria. Since 1977, Thailand's environmental policies have been included in the National Economic and Social Development Plan. Furthermore, in the 12th edition (2017–2021), the country's environmental strategy was prepared based on both the 20-year National Strategy Plan framework (2017–2036) and the SDGs (Office of Natural Resources and Environmental Policy and Planning 2017). Numerous aspects regarding potential wastewater reuse and improvements to the associated treatment process continue to be the object of research collaboration and innovation in Thailand.

Thirty-five research works on wastewater treatment and recycling technology in Thailand over the past 10 years were reviewed and summarized in Table 6, categorized by the type of wastewater sources. Opportunities and challenges are also presented, allowing us to draw the following conclusion. Most previous research related to domestic wastewater treatment has focused on the development of advanced biological treatment systems so that they can be more effective in treating organic matter, nutrients (N, P) and micropollutants by the MBR system as a complement to the overall treatment. However, the development of membrane materials for the system has yet to be studied.

There is some research focused on the development of municipal wastewater treatment to reduce contamination of antibiotics and pharmaceutical products by advanced materials, such as photocatalysts and adsorbents, most of which are still in laboratory research. The contamination of antibiotics and pharmaceutical products is a big challenge for wastewater reclamation in Thailand due to the low removal efficiency of the current WWTPs. Contamination with 11 of 15 antibiotics was reported in both influent and effluent wastewater samples from the AS municipal WWTP in Thailand. The removal efficiency of antibiotic contamination depended on the type of antibiotic. For example, the AS system could treat up to 100% of

Table 5 | Common problems when operating municipal WWTPs in Thailand

Households	Collection pipe system	Municipal WWTPs	Distribution systems for wastewater reclamation
-Some communities have not installed preliminary wastewater treatment devices, leading to large amounts of O&G in the influents to WWTPs.	-Collecting pipelines do not cover all community areas yet. -Expanding the construction of collecting pipe systems in dense communities and alley areas is difficult, as there is almost no space for pipe laying. -Garbage often blocks the grates at the sewage pumping station, causing damage to the pump. -The sewage pipe is clogged by sand sediment. -Sewage pipes under roads are often broken and damaged, causing wastewater to be collected below the designed volume. -Insufficient water collection pipes in the rainy season cause flooding, and the collection pipe system is damaged. -In community areas near the sea, there are often problems with seawater flowing into the sewage pipe system (e.g., flap gates), causing damage to machinery and equipment. -Lack of budget for system monitoring and maintenance.	-Wastewater input is significantly less than the designed capacity. -Due to the depletion of the wastewater level during the dry season, the pond edge collapses. -During the dry season, some parameters cannot meet the water quality standard due to the lower flow rate, the long retention time, algae blooming on the surface causing less DO, higher SS and a bad smell in the effluents. -A large amount of bottom sediment accumulates in the ponds, causing the treatment efficiency to decrease. -Total coliform bacteria and fecal coliform bacteria are detected in the effluents from the last pond with relatively high values, causing water reuse problems. -Sedimentation in the polishing ponds is ineffective due to people trespassing into the ponds in order to fish. -During the dry season, wastewater is illegally pumped from WWTPs for agricultural watering. -Lack of nearby laboratories for wastewater quality analysis. -Lack of specialized personnel for operations and maintenance. -Lack of statistical data on the flow rate of wastewater entering WWTPs, causing operations to become ineffective. -Lack of budget for system maintenance.	

Sulfamethoxazole, Lincomycin, and Clarithromycin, while the system could treat only 62.43 and 8.49% of Ciprofloxacin and Norfloxacin, respectively (Eaktasang *et al.* 2021). This was consistent with the results studied by the Department of Environment Quality Promotion in 2016, which found contamination of Ciprofloxacin and Norfloxacin in water samples from Bang Pakong River (Sawatyothin *et al.* 2016). The potential spread of antibiotics from WWTPs to contaminants in the environment could cause ecological effects such as a decrease in population in the ecosystems, causing an imbalance in the food chain, and affecting human health as well (Roig & D'Aco 2016; Ebele *et al.* 2017) Therefore, Thailand needs to expedite the laboratory research to integrate with the existing bio-WWTPs such as advanced oxidation process (AOP), membrane separation, photocatalytic treatment, and sonication (Manoharan *et al.* 2022). This will enhance the efficiency of the biological WWTPs to be able to eliminate antibiotics and pharmaceutical products to control pollution at the source effectively.

According to 35 literature reviews in Table 6, some research focused on the development of wastewater treatment for the textile industry. The textile industry consumed a lot of water and chemicals in the production and was the third largest

Table 6 | Research trends regarding wastewater treatment technologies, along with opportunities and challenges in Thailand

No	Type of wastewater	Type of wastewater treatment	Purpose	Opportunities/challenges	Ref
1	Municipal	AS	To test the efficiency of systems against 19 common biocides present in wastewater	Efficiency of systems was reported as removal rates ranging from 15 to 95% for individual biocides. Reuse for aquaculture showed high risks of exposure to biocides in aquatic organisms.	Juksu *et al.* (2019)
2	Municipal	Contact stabilization, AS with nutrient removal, cyclic AS, two-stage AS, vertical loop reactor AS	To assess the treatment efficiency for removal of organic matter and nutrients	All systems achieved over 80% BOD removal efficiencies. The maximum removal efficiencies of BOD, TP, TN, TKN, NH_4-N were observed to be satisfactory, being 93, 69, 60, 83 and 89%, respectively. However, incomplete denitrification was a problem for contact stabilization. Denitrification was required for any type of reuse.	Prateep Na Talang *et al.* (2020)
3	Municipal	AS	To investigate the potential risks of 14 pharmaceutical residues from municipal WWTPs in Bangkok	Pharmaceutical residue removal efficiencies ranged from nil to >99%. Three kinds of residues (roxithromycin (RTM), diclofenac (DCF) and sulfonamides) showed very low or no removal. However, the residues in effluents were lower than those detected in ambient water, implying that contamination from WWTPs was negligible.	Tewari *et al.* (2013)
4	Municipal	AS	To investigate the occurrence and fate of emerging contaminants (four synthetic musks and nine UV filters) as ingredients in personal care products in Bangkok and Pattaya, Thailand	Low removal efficiencies, ranging from 37 to 58%, were found for four musks, while UV filters showed higher removal efficiencies, ranging from 45 to 81%. The concentrations detected in this study were much higher than those reported elsewhere in the world. Further treatment for these emerging contaminants is required for specific reuse purposes.	Juksu *et al.* (2020)
5	Municipal effluents	Bacterium cell-immobilized biochars from wood vinegar	To improve the removal efficiency of triclocarban (TCC), an emerging endocrine disruptor	Biochar with MC46 cells was more effective in TCC removal than biochar without MC64, due to the greater integration of adsorption and	Jenjaiwit *et al.* (2021)

(*Continued.*)

Table 6 | Continued

No	Type of wastewater	Type of wastewater treatment	Purpose	Opportunities/challenges	Ref
				biodegradation. A TCC removal efficiency of 79.8% was achieved. A reduction in removal efficiency of 52% occurred after a five-reuse cycle. The biochar could be successfully used for reclamation in terms of the removal of emerging pollutants.	
6	Municipal	Photocatalytic process	To develop a ZnO/Bi_2WO_6 heterojunction photocatalyst for the removal of fluoroquinolone-based antibiotics (norfloxacin (NOR), ciprofloxacin (CIP), and ofloxacin (OFL))	Photodegradation performances of 87, 85 and 84% for NOR, CIP and OFL, respectively, were achieved from the synthesized catalyst. Photodegradation performance of NOR was satisfactory with 97% under a very high solar-light-driven for 120 min. The applied catalyst proved promising for fluoroquinolone-based antibiotics in wastewater.	Chankhanittha *et al.* (2021)
7	Domestic	Biofilm photobioreactors (BPBRs)	To ascertain the optimum operating conditions for the removal of organic and nutrient load (N,P) from septic tank effluent	The optimum conditions were obtained as the 6-day hydraulic retention time (HRT), resulting in COD, TN and TP removal efficiencies of 85, 87 and 84%, respectively. COD in effluents was still high and required further treatment for agricultural reuse.	Chaiwong *et al.* (2021)
8	Domestic	Electroconductive moving bed membrane bioreactor (EcMB-MBR)	To investigate the simultaneous removal of COD, TN and TP	Removal of COD (97%), TN (88%) and TP (99%) by the EcMB-MBR process was higher than that of conventional submerged MBR. The EcMB-MBR process was able to improve membrane fouling mitigation. This system may be helpful in producing reusable water via decentralized domestic wastewater treatment.	Udomkittayachai *et al.* (2021)
9	Domestic	Inclined tube settler + sand filter + ultraviolet light-emitting diode (UV-LED)	To investigation the appropriate conditions and removal efficiency of COD, turbidity and TSS.	This system treatment was applied to meet U.S. EPA criteria for disinfecting water for agricultural use. The pretreatment by the inclined tube settler and sand filter was successfully	Nguyen *et al.* (2019)

(*Continued.*)

Table 6 | Continued

No	Type of wastewater	Type of wastewater treatment	Purpose	Opportunities/challenges	Ref
				used to decrease COD by 89.9%, turbidity by 94%, and TSS by 96.8%.	
10	Domestic	Fats, Oil and Grease (FOG) trap + sediment microbial fuel cells (SMFCs)	To determine optimally constructed single-chamber SMFCs for household application	A COD removal efficiency of 85.8% and a maximum power density of 109.39 mW/m^2 were obtained with activated carbon (AC) in the cathode chamber. The direct reuse of effluents was limited.	Lawan *et al.* (2022)
11	Domestic	SP + constructed wetland (free water surface (FWS)-CW)	To develop a mathematical model for soluble COD (sCOD) removal process by CW	sCOD leaching from the gravel bed was the main mechanism affecting the sCOD concentration in the treatment system. To prevent sCOD leaching, the suitable HRT should not exceed 2 days. This CW showed potential for dissolved organic matter (DOM) removal, but proved highly sensitive to the HRT. Tertiary treatment is suggested to reduce DOM before reuse.	Ophithakorn *et al.* (2013)
12	Domestic	Absorption by porous floating *Meretrix lusoria* shell composite (PFSC)	To develop PFSC pellet adsorbents for the removal of phosphate and nitrate	Removal efficiency of phosphate was satisfied with >99% by PFSC. Bacterial immobilized PFSC removed 100% of phosphate and nitrate. PFSC pellets were able to float on the water surface and were easily collected and reused. A low-cost treatment to improve effluent quality was achieved in terms of nutrient removal.	Daudzai *et al.* (2021)
13	Domestic	Membrane-aerated biofilm reactor (MABR)	To enhance organic matter and total N removal efficiency by MABR with denitrifying bacteria	The improvement of TN removal efficiencies was satisfactory by modified MABR, and >90% organic matter removal, 88% nitrification and 79% total N removal efficiencies were obtained at 12 h of the HRT.	Siriweera *et al.* (2021)
14	Domestic/Building	Integrated single-stage anaerobic co-digestion and oxidation ditch membrane bioreactor (SAC/OD-MBR)	To evaluate the appropriate conditions and efficiency of the SAC/OD-MBR	The highest removal efficiencies of COD and TKN-nitrogen were achieved at 93.77 and 85.57%, respectively, with an operating HRT of 24 h and a horizontal flow velocity of	Satayavibul & Ratanatamskul (2021)

(*Continued.*)

Table 6 | Continued

No	Type of wastewater	Type of wastewater treatment	Purpose	Opportunities/challenges	Ref
				0.3 m/s. Effluent quality is suitable for reuse in garden and landscape applications.	
15	Domestic/ Dormitory	MBRs	To demonstrate reclaimed water's potential for flushing toilets and cultivating vegetables	The quality of the treated water fell within the guidelines. The growth of vegetables (butterhead lettuce and muskmelon) from treated water compared to tap water was not significantly different.	Itthisuponrat & Teepakpun (2021)
16	Industrial estate	AS + polishing pond, SBR	To determine processes' performance regarding the removal of PFCs	The AS process proved ineffective in removing PFCs. The overall removal efficiency was about 22–70%. Tertiary treatment is required for indirect potable reuse.	Kunacheva *et al.* (2011)
17	Synthetic textile	RO	To determine foulant interaction (salt, surfactant, reactive dye) and RO productivity	During textile wastewater reclamation, surfactant was the major cause of membrane fouling. The lowest productivity was observed when the surfactant concentration approached the critical micelle concentration.	Srisukphun *et al.* (2010)
18	Direct Dye dyeing	Photocatalytic process by immobilized TiO_2 nanoparticles under UV-A	To develop TiO_2 material for the removal of direct dye	A dye removal efficiency of 64% at 4 h was achieved from immobilized TiO_2 calcined at 700°C. The dye removal efficiency of second reused catalyst remained high. The potential reuse of treated wastewater by this catalyst within the dyeing process is suggested for small dyeing facilities.	Chairungsri *et al.* (2022)
19	Textile and pharmaceutical	Photocatalytic process by hydrothermal ZnO under UV light irradiation	To develop ZnO photocatalysts for the removal of organic pollutants, including dyes and antibiotics	The complete photodegradation of organic pollutants during 20–180 min under solar light irradiation was obtained from hydrothermal ZnO with a Zn^{2+}/OH^- mole ratio of 1:5. The applied catalyst is promising for the detoxification of organic pollutants in wastewater.	Sansenya *et al.* (2022)
20	Cationic and anionic organic dye	Photocatalytic process	To develop photocatalysts made from Na0.5Bi2.5Nb2O9 nanosheets with exposed	A superior degradation efficiency of up to 100% compared with a TiO_2 degussa P25 was obtained	Jiamprasertboon *et al.* (2021)

(*Continued.*)

Table 6 | Continued

No	Type of wastewater	Type of wastewater treatment	Purpose	Opportunities/challenges	Ref
			{001} facets for photodegradation of dye	from the synthesized materials, and exhibited high stability and recyclability.	
21	Organic dye	Absorption by activated carbon	To develop AC made from parawood and to study photoadsorption's ability under UV light	The optimum conditions for adsorption capability were obtained with a 5 wt% activated carbon sheet, and exhibited excellent stability and recyclability in five tests.	Chaiwichian & Lunphut (2021)
22	Organic dye	Electrochemical oxidation (ECO)	To evaluate the energy efficiency and decolorization performance of dyebath effluents containing anthraquinone dye Acid Green 25	Color and COD were reduced to below-discharge limits using 100 mA cm^{-2}. The aromatic ring was broken into biodegradable substances (carboxylic acids, ammonium, nitrate). The applied ECO system is promising for non-potable reuse purposes in small- and mid-sized textile facilities.	Phetrak *et al.* (2020)
23	Dye	AOPs: photocatalytic process	To develop a TiO_2 photocatalyst, synthesized by sol-gel and coated on different substrates	A maximum color removal efficiency of 88% was achieved by TiO_2-coated glass under UVC irradiation at pH value 11. The same removal efficiencies were obtained in up to 20 cycles.	Sirirerkratana *et al.* (2019)
24	Food processing	Anaerobic membrane photo-bioreactor (AnMBR)	To investigate organic removal and biomass production (purple non-sulfur bacteria) and its characteristics	BOD and COD removal efficiencies were found at the moderate range of 51 and 58%, respectively. Further treatment is required for reuse purposes.	Chitapornpan *et al.* (2013)
25	Seafood	MBR	To evaluate the removal efficiency of organic matter and nutrients	The removal efficiency of BOD was 99%, compared to only 85% for COD and TOC, during 1,000 h of filtration. TKN removal was very low (close to 5 mg/L). It was necessary to remove residual COD and the yellow light color in the permeate before water reuse by further treatment.	Choksuchart Sridang *et al.* (2006)
26	Swine	AOPs based on Fenton by reactive iron-coated natural filter media	To develop low-cost natural materials (zeolite, laterite and pumice) for the removal of veterinary antibiotics	>50% of antibiotic removal was obtained from every iron-coated medium at a neutral pH. The modified zeolite exhibited the highest antibiotic removal efficiency of >70% with at least three	Changduang *et al.* (2021)

(*Continued.*)

Table 6 | Continued

No	Type of wastewater	Type of wastewater treatment	Purpose	Opportunities/challenges	Ref
				times reuse. It is suggested that this material be applied as a polishing step, such as in soil bed filtration and CW before water reuse.	
27	Swine	Conventional anaerobic treatment with adsorbent	To investigate porous metakaolin-based geopolymer granules with tailored macropore structure for ammonium removal	An ammonium removal efficiency of 80% was achieved from the synthesized material even with the presence of organic compounds and competing ions, much improved from natural zeolite (46%).	Sanguanpak *et al.* (2021)
28	Rubber	AS + stabilization pond + rock bed filtration	To improve the COD, BOD and turbidity quality of reclaimed wastewater	TSS, BOD and COD removal efficiencies of 89.6, 73.7 and 45.6%, respectively, were obtained by rock bed filters. However, further treatment is suggested to remove the residual organic matter and nutrient to meet water reuse criteria.	Leong *et al.* (2003)
29	Eucalyptus pulp and paper mill	MBRs	To investigate the fouling of polyvinylidene fluoride (PVDF) MBR and COD and color removal performance	COD and color removal efficiency were satisfied with 83 and 79% at mixed liquor suspended solids (MLSS) of 7,280 mg/L. Effluent quality was able to meet discharge standards, with the potential for water reuse. Cleaning with NaOH and NaOCl was necessary to remove the irreversible fouling.	Poojamnong *et al.* (2020)
30	WW from flexible PCB	Ion exchanger + RO	To evaluate washed water reuse in a factory by surveying water consumption and quality	Water reuse for the final cleaning process of F-PCB proved feasible by recharging the washed water to both the existing RO unit and the ion exchanger at a suitable ratio to reduce conductivity and liquid particle counter.	Eksangsri & Jaiwang (2014)
31	Industrial lead-acid battery	Absorption by cation exchanger impregnated with nanoparticles	To develop hydrated ferric hydroxide nanoparticle (C100-Fe) adsorbents for the removal of lead	Lead in effluent was treated to less than 0.2 mg/L by applied C100-Fe in coprecipitation with high lead recovery (94%) during regeneration. Lead removal was achieved according to both drinking and industrial wastewater standards. Cost-effective and reliable Pb	Pranudta *et al.* (2021)

(*Continued.*)

Table 6 | Continued

No	Type of wastewater	Type of wastewater treatment	Purpose	Opportunities/challenges	Ref
				removal adsorbents were achieved.	
32	Lignite coal mine drainage	Ettringite precipitation	To determine the optimum conditions for sulfate removal	The significant factors affecting sulfate removal efficiency were the Al/S ratio and the reaction time. A sulfate removal efficiency of 99% was achieved under a reaction time of 6.14 h, a Ca/S of 4 and an Al/S of 4.5 at ambient temperature. Treated water could be utilized for agricultural purposes.	Pratinthong *et al.* (2021)
33	Phenolic	Ozonation and granular activated carbon (GAC) adsorption by fluidized bed	To determine the optimum conditions for phenol removal and an adsorption kinetic model	Phenolic degradation using GAC enhanced with O_3 provided better performance than the system without O_3.	Pratarn *et al.* (2011)
34	Municipal landfill leachate effluent	Two-stage AS and two-stage MBR	To investigate the treatment efficiency of two treatment systems for the removal of organic compounds, nutrients and micropollutants (BPA, 2,6-DTBP, DEP, DBP, DEHP, DEET).	The removal efficiencies for the organic compounds and nutrients of both systems were 80–96%. The micropollutant removal efficiencies of MBR (81–100%) were higher than those of AS (45–87%). MBR with acclimatized seed sludge was more effective in degrading micropollutants than AS, due to the greater abundance of effective bacterial groups. The MBR system is promising for reducing micropollutants for wastewater reclamation.	Kanyatrakul *et al.* (2020)
35	Chemistry laboratory	Absorption by white and black charcoal	To reduce COD and adjust pH to neutral	White charcoal was able to neutralize the pH after treatment in both acidity and alkalinity wastewater, and 97–99% COD removal efficiency was achieved from both charcoals.	Pijarn *et al.* (2021)

PCB, Printed circuit boards; N, Nitrogen; AC, Activated carbon; CW, Constructed wetlands; AOPs, Advanced oxidation processes; BPA, bisphenol A; 2,6-DTBP, 2,6-di-tert-butylphenol; DEP, diethyl phthalate; DBP, dibutyl phthalate; DEHP, di(2-ethylhexyl) phthalate; DEET, N,N-diethyl-meta-toluamide.

wastewater discharge industry in the country (Panthong 2017). Most of the pollutants contaminated in wastewater come from bleaching and dyeing processes, where only some portion of the dyes used in this process is trapped on the surface of the yarn and the rest will be mixed with wastewater. Consequently, most of the research found in Thailand focuses on decolorization in wastewater, because even a small amount of color in wastewater can still be seen clearly and be an obstacle to water recycling. There are many types of dyes used in the textile industry, such as reactive dyes, acid dyes, basic dyes, direct dyes, vat dyes, disperse dyes, etc. Some types of dyes are easily decomposed by conventional physical and chemical WWTPs, while some types are difficult to decompose due to their complex chemical structure, such as azo compounds. Their intermediates are aromatic amines, which are carcinogenic and toxic to living organisms (Saratale *et al.* 2011). Most of the WWTPs used in the textile industry in Thailand were physical treatment, physicochemical treatment, and biological treatment; however, their color removal efficiencies were still low. Moreover, there were also many limitations in developing treatment technologies, especially the cost of treatment and sludge treatment (Sirianuntapiboon 2018). The challenges related to textile wastewater treatment lead to opportunities for various research and technology development in Thailand such as biological methods, AOP, electrocoagulation, adsorption, membrane technology, and photocatalytic reactors using novel nanomaterials (Samsami *et al.* 2020), which can improve the decolorization efficiency of the current industrial WWTPs and increase the water reclamation opportunity in the production process.

By contrast, there is still little research on the development of WWTPs for municipal landfill leachate in Thailand. The pollutants usually found in landfill leachate are a wide range of both toxic organic and inorganic substances such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), phenolic compounds, pesticides, pathogenic organisms, microplastics, and pharmaceuticals, most of which can be persistent in the environment (Bandala *et al.* 2021). However, the quality control standard of effluent from leachate treatment systems in Thailand has not regulated some emerging pollutants (such as POPs, PFAS, and antibiotics) by law (Kanchanapiya & Tantisattayakul 2022) and it can pose significant risks to the ecosystem and human health. Currently, a lack of research funding has likely resulted in insufficient analyses of emerging pollutants, removal efficiency from landfill WWTPs. Therefore, the governmental supportive measures and cooperation from the stakeholder are essential for coping with challenge and enhancing opportunities to promote wastewater reclamation in this sector.

WASTEWATER REUSE OPPORTUNITIES

Thailand is a developing country that is seeing sustained economic growth. The gross domestic product (GDP) contributions of different sectors are as follows: agriculture 8.2%, industry 36.2%, and services 55.6% (Central Intelligence Agency 2017). As shown in Figure 2, the recycling of treated wastewater from municipal WWTPs is less than that from industrial WWTPs, presenting a great opportunity to expand the utilization of such wastewater in order to support economic growth. Moreover, on-site wastewater recycling systems in individual households are rare, which implies that there still is an opportunity to strengthen the measures for the residential sector. The selection of a wastewater treatment method for a wastewater reclamation project depends on many factors related to the project area, for example meteorological data, water resources, topography, land use, community occupation and acceptance, community awareness of drought, cultural norms, and religious beliefs (ISO 2018a). In addition, regulations related to wastewater reclamation, including planning and encouraging local authorities' projects, are important, along with central government financing under the 20-year National Strategic Plan. Increasing water demand – coupled with the suffering caused by droughts occurring in some areas and at certain times – has provided the impetus for local authorities to promote the renovation of existing WWTPs. Furthermore, the construction of a new WWTP that reuses wastewater has become a top investment priority.

Given the discovery of various emerging pollutants (e.g., POPs, PFAS, heavy metals, pesticides, antibiotics, flame retardants, viruses) in wastewater resources worldwide (Schultz *et al.* 2006; Kunacheva *et al.* 2011; ISO 2018a; Wang *et al.* 2021), responsible agencies are being pushed to revise regulations related to the quality of effluent from WWTPs, in order to cover the health risks posed by these emerging pollutants. This is leading to opportunities to expand commercially available advanced technologies for WWTPs, as well as recycling, such as membrane filtration, electrochemical treatment, ultraviolet (UV) radiation, oxidation processes, photocatalysts, and granular activated carbon (GAC) adsorption. With the support of government budgets and local governments' collection of wastewater treatment fees (Pollution Control Department 2020), as well as clear policies regarding wastewater reclamation in the industrial sector, the advanced treatment systems may become economically feasible, which will enable the growth of the wastewater recycling market. The significant opportunities available for the future development of wastewater reclamation to reduce water scarcity in Thailand are explained in the following sections.

Wastewater reuse in agriculture

Thailand has a total agricultural area of approximately 238,400 km^2, accounting for up to 46.5% of the country's area (Office of Agricultural Economics 2019). WWTPs located in agricultural areas hence have high potential to reuse their effluent. However, the reuse of wastewater for irrigation has not been taken seriously to alleviate water shortages, especially during the annual dry season. The benefits of recycling wastewater for agriculture have been discussed in view of circular economics, and are stated in SDG 6 as a means of addressing water scarcity (Guerra-Rodríguez *et al.* 2020). The wastewater treatment sector can apply the circular economy concept for a growing water security opportunity, for example, the reuse of wastewater to increase water resources, by paying particular attention to the risks to human health, the recovery of nutrients or high-value-added products (e.g., metals and biomolecules), the valorization of sewage sludge, and/or the recovery of energy (Rodriguez *et al.* 2020). Although wastewater recycling increases water supply and often contains essential nutrients for plants, resulting in reduced demand for fertilizer, there are also concerns about human health risks from residual pollution that are not covered in the effluent quality standards of municipal WWTPs, such as heavy metals, medicines, hydrocarbons, POPs, pesticides, micropollutants, pharmaceutical compounds, and personal care products (Guerra-Rodríguez *et al.* 2020; Singh 2021).

In Thailand, the Royal Irrigation Department issued a standard for the quality of sewage discharged into irrigation waterways to prevent poor-quality drainage from industrial and urban expansion since 2011 (Royal Irrigation Department 2011), which has additional parameters on heavy metals and pesticides and so on more than the effluent quality standard of municipal WWTPs, reflecting how residual pollutants are monitored in its irrigation system, as shown in Table 2.

Thailand has issued water quality standards for surface water sources, divided into five categories since 1994 under the National Environmental Quality Promotion and Conservation Act. These cover the quality of water sources that receive wastewater from certain activities that can be used for agriculture, as well as the limitation of heavy metals, pesticides, and coliform bacteria (National Environment Board 1994). Given that Thailand currently has no criterion for the quality of reclaimed wastewater in the agricultural sector, surface water quality standards for agriculture or industrial effluent standards are recommended as a reference criterion for wastewater reuse in agriculture instead (Department of Industrial Works 2021).

The results of survey and evaluation reports regarding Thai municipal WWTPs' reuse of treated wastewater at the provincial level from 2013 to 2017 are presented in Table 4 (Office of the Environment Region 1-16 2016; Pollution Control Department 2017b; Office of Strategy and Evaluation 2020). During this period, most of the treated wastewater was discharged into nearby canals, creeks, rivers or seas, and these effluents were available for indirect reuse in the agricultural sector (reuse through a receiving body). Thirty-one out of 55 provinces (56%) found that some of the treated wastewater was directly reused in the agricultural sector, especially during the dry season, such as agricultural and gardening irrigation (e.g., rice fields, lotus plants), plant mangrove forests (aquatic breeding grounds), livestock uses, and fisheries. Analyses of drought-affected agricultural areas and irrigation management from nearby treated wastewater should be effectively harmonized to increase crop production and the proportion of wastewater reuse at the province level.

Despite the current effluent quality control standards regarding municipal WWTPs, there are still some parameters that are not regulated according to the surface water standards for agriculture, as shown in Table 3. As a result, most of the effluents from WWTPs are not suitable for direct use in the agricultural sector, especially due to the presence of pathogens. According to Table 4, only 31 of the 104 WWTPs (representing 30% of the total) have disinfection systems, most of which have included a chlorine unit after the final treatment pond. Such disinfection systems deserve additional investment to ensure the safe consumption of vegetables planted with treated wastewater. Although there are still no legal discharge limits for some organic micropollutants and endocrine-disrupting chemicals (EDCs), such as pharmaceuticals, hormones, antibiotics, pesticides, UV fillers, antioxidants, phthalates, and PFAS (Barbosa *et al.* 2016) – another modern threat to WWTPs' effluent resources in Thailand – improving wastewater systems should take into account the risks to human health posed by these pollutants.

Urbanization

Urbanization often results in increased water demand, leading to larger amounts of wastewater released to water sources. As of September 2021, the current population of Thailand is about 70,014,000, meaning that the country accounts for approximately 0.9% of the world's population, ranking 20th overall. The population density in Thailand is 97 people per km^2. Reflecting the extent to which urbanization has occurred here, in 2021 approximately 51% of the population lived in urban areas, whereas in 1960, this was true of only 20% (Worldmeter 2021). Thailand has one city with more than one million people, 19 cities with between 100,000 and one million people, and 265 cities with between 10,000 and 100,000 people. The largest city is the capital, Bangkok, with a population of up to five million people (World Population Review 2021). Developments are clearly concentrated in Bangkok, while in other cities the central government focuses on developing only certain sectors, for example industry in eastern provinces such as Chonburi, Rayong, and Chachoengsao, and tourism in southern provinces like Songkhla and Phuket (Janbuntha & Janpuengpon 2018). At present, Bangkok has eight central WWTPs – more than any other province – with a total treatment capacity of 1.11 mil.m^3/day, almost 50% of the country's wastewater treatment. In 2020, Bangkok was only able to reuse 7.2% of its treated water. More than 50% of this water was reused for landscaping outside the WWTPs (for watering plants in public gardens), and the remainder was reused inside the WWTPs themselves (for washing machines and floors). Treated wastewater was transported from the WWTPs to public gardens via either pipes or trucks, depending on the area's topography, costs, and the readiness of the relevant agencies (Strategic and Evaluation Office 2020). There are further opportunities to improve the quality of effluent with advanced technology for other reuse purposes in Bangkok, such as for cooling air conditioners, replacing groundwater supply due to a prohibition on extracting groundwater in Bangkok, and replacing raw water in tap water plants.

Besides Bangkok, the industrial eastern region (especially the provinces of Chonburi, Rayong, and Chachoengsao) is home to 16 municipal WWTPs with a total treatment capability of 0.21 mil. m^3/day, accounting for nearly 10% of the country's wastewater treatment. Most of these WWTPs are equipped with chlorine disinfection systems, and wastewater is mostly reused for green space irrigation and washing garbage trucks. In addition, there are many industrial estates located in this industrial region, containing a total of 32 central WWTPs (Table 4) (Industrial Estate Authority of Thailand undated), six of which have already installed membrane systems (MF, UF, RO) to improve effluent quality, so that it can be recycled as part of the production process within factories, especially during the dry season. Factories with high water demand per unit product (e.g., textiles and garments) should be encouraged to recycle more water during the production process (Industrial Estate Authority of Thailand).

It is obvious that during the dry season, there is not enough water supply for both the community and industrial sectors in some urban areas of Thailand. Thus, it is necessary to boost water resource efficiency by promoting wastewater reclamation to large cities first. For example, the Drainage and Sewerage Department of Bangkok has set a target of treated wastewater utilization in communities of about 6.6% for 2022, and this percentage is continuously increasing every year (Office of Strategy and Evaluation 2021). In addition, an eastern industrial estate in Chonburi has initiated a project to improve its water resource efficiency by applying RO technology in wastewater reclamation and desalination and managing water resources, and analyzing integrated data from weather forecasts and surface water and groundwater sources. As a result, water resources may be reduced by approximately 35–40% (World Population Review 2021). Similar initiatives are being realized in other industrial estates for the cost-effective reuse of wastewater, especially in Thailand's Eastern Economic Corridor (the EEC region) (Water and Environment Institute for Sustainability 2019).

Water stress and climate change

Climate change is the major cause of extreme heat, droughts, heavy rain and floods worldwide, and Thailand is facing the same problems as many other countries in Asia (Miyan 2015; Mukherjee *et al.* 2018). Koontanakulvong & Chaowiwat (2010) have forecast changes in rainfall in near (2015–2039) and distant future (2075–2099) scenarios according to three regional climate models (RCMs) (Thailand Climate Change Adaptation Information Platform). Their calculations indicate that rainfall is expected to either increase or decrease in different regions of Thailand. The near future will see less rain than at present, but in the distant future this trend will reverse. However, increasing temperatures (0.015–0.047 °C per year) in the Chao Phraya River Basin will result in greater demand for water in this region, increasing its risk of drought (Koontanakulvong & Chaowiwat 2010; Thailand Climate Change Adaptation Information Platform). Furthermore, Koontanakulvong & Chaowiwat (2010) study of rainfall changes at the watershed level in both Thailand and China indicates that both the peak flow of rain and the overall amount of water in the upper and lower courses of the main river of Thailand's Yom Basin will be lower than the current figures (Thailand Climate Change Adaptation Information Platform). Such reductions in rainfall may pose problems for Thai water management in the future. In fact, due to decreased rainfall from 2005 to 2013, the number of repetitive drought areas has increased in recent years. This drought problem will exacerbate existing economic pressures in Thailand through damaging the agricultural sector, which in 2020 had the highest water demand (75% of total water consumption, particularly for sugar, rubber, and rice). Indeed, the total economic cost of droughts in this year was about US$ 1.5 billion, or 0.27% of the country's GDP (Manorom 2020).

To negotiate the effects of climate change, the United Nations Framework Convention on Climate Change (UNFCCC) recommends IWRM strategies, including developing water-saving technologies, increasing water productivity, and reusing water (UNFCCC 2014). Global Climate Action, launched in 2014 by UNFCCC, has established a wastewater goal for a zero-carbon future: 100% of all municipal, industrial and agricultural wastewater is to be treated for reuse or discharge into the environment through a decentralized modular wastewater treatment process by 2040 (Global Climate Action and Marrakech Partnership 2020). In other words, changes in water recycling for both the industrial and household sectors in Thailand have been catalyzed by global climate change policies to restrain the increasingly unfair distribution of water resources between the industrial and agricultural sectors. In particular, Thailand should issue regulatory standards for wastewater reclamation that cover various usages and accelerate the expansion of commercial and cost-effective technologies such as membranes (ISO 2021), especially in industrial estates where significant water security is required for production.

Wastewater reuse market

The opportunities from exploiting wastewater as a valuable resource to support the increasing demand for freshwater are enormous. Several potential uses may help reduce freshwater consumption, such as reuse within an industry via closed loop water recycling, and the recharging of aquifers to replenish groundwater, of benefit to cleaning streets and garbage trucks, and watering plants, gardens, and golf courses (U.S. EPA 2012). However, although wastewater reclamation has many benefits, wastewater reclamation is often questioned, as rising costs hinder the market expansion of wastewater reuse. To enable the wastewater reuse market to grow sustainably, it is necessary to show investors the economic value of additional investment. In other words, the most effective marketing strategy for wastewater reuse is to transform the general image of wastewater from a source of pollution to a clean, safe and economically attractive resource (Roy *et al.* 2011). The United Nations Environment Programme (UNEP) has provided a guideline for assessing the economic value of wastewater according to economic, environmental, social and health perspectives (Hernández-Sancho *et al.* 2015). Moreover, cost-benefit analysis (CBA) and life-cycle assessment (LCA) (Rodriguez-Garcia *et al.* 2011) are available tools for evaluating wastewater reclamation projects, which take into account financial and environmental costs (Rodriguez-Garcia *et al.* 2011).

Since 1992, Thailand has initiated financial tools for sustainable wastewater management, specifically the polluter pays principle and public participation (Ministry of Natural Resources and Environment 2010). In 2020, local government organizations collected treatment fees based on annual operating and maintenance costs (excluding the land and construction costs mostly invested by the central government), enabling them to have income available to maintain about 30 sites of municipal WWTPs (accounting for 16% of the total number of WWTPs) by themselves (Pollution Control Department 2020, 2021).

Although over a 60-year period (1955–2014) the accumulated rainfall in Thailand from May to October did not show significant change, and from November to April it even increased by 10.8 mm/decade (The World Bank Group 2021), some areas still suffered from water shortages in the agricultural sector, as shown in Figure 1. This presents an opportunity to expand the wastewater reclamation market. Moreover, only 15% of the total water consumed in urban areas – especially around the lower Chao Phraya River, where Bangkok is located – is treated in WWTPs, raising concern that Thailand will not achieve SDG 6 (UN 2015). This presents a need to invest in wastewater treatment systems that integrate water recycling technology, in order to increase Thailand's total wastewater treatment capacity.

To support the expansion of the country's industrial and tourism sectors, Thai government agencies have offered more opportunities to the private sector to invest in water management, for example, tap water production from surface water, seawater, and municipal wastewater in water shortage areas under the Public-Private Partnership Act B.E. 2562 (Thai government 2019). Such joint investment can reduce the burden of the government investment budget and change the role of the government sector from being an operator to a regulator, thereby increasing efficiency in management. Joint investment contracts between private and government agencies to manage the water business mostly exist in the form of 15–30-year concession contracts, such as build-transfer-operate (BTO), build-own-operate-transfer (BOOT), build-lease-operate-transfer (BLOT), and build-rent-own-transfer (BROT) (Parliamentary Budget Office 2016). In addition, if discharging unqualified effluents are charged, the reduction of costs associated with environmental tax on wastewater discharge is another driving force for the expansion of the wastewater reclamation market (Ryan 2016). For this issue, the regulations regarding wastewater discharge need to be reviewed and revised.

Groundwater exploitation

Groundwater is a water resource that is often more expensive than surface water due to the drilling and pumping costs involved. However, Thailand is dependent on groundwater for consumption in agriculture and industry, especially in drought situations, when there is a lack of surface water. Thailand has a total groundwater storage volume of up to 1.13 trillion m^3 from a total of 27 groundwater basins, with annual potential utilization standing at 68,200 million m^3 (Water Resources Policy and Management Committee 2015). Thailand continually faces a quantitative and qualitative groundwater crisis due to over pumping. In 1977, the Groundwater Act was passed to protect the quantity of groundwater through controlling groundwater licensing, groundwater utilization and water infiltration to wells. Furthermore, in 2019 the Department of Groundwater Resources set a standard for filling the shallow basement (the unsaturated soil layer) to cope with drought.

Filling water into groundwater is limited to rainwater and surface water (Department of Groundwater Resources 2019) and hence does not include treated wastewater. Incorporating treated wastewater into groundwater storage is an attractive alternative and opportunity for wastewater reclamation in the industrial sector to reduce the risk of water shortages during the dry season. However, Thailand has no standard to carry out such activity in both urban and industrial zones to ensure that groundwater is safe for the environment and long-term health.

Tourism

Tourism is an important economic sector in Thailand, comprising businesses such as hotels, resorts, and guesthouses. In 2019, the GDP from accommodation and food service activities was valued at US$ 30.3 billion, accounting for 6.1% of the country's total GDP (Krungsri Bank 2019). Growing tourism has led to a need for more WWTPs to accommodate the increasing wastewater volume from buildings and facilities. In 2018, the Designated Areas for Sustainable Tourism Administration in Thailand released the Sustainable Tourism Management Standard, which includes the promotion of water reuse in tourist accommodations (Designated Areas for Sustainable Tourism Administration (Public Organization) 2018). As shown in Table 2, through this standard such wastewater must be treated in an on-site wastewater system to improve its quality before being released to the outside. Nevertheless, marinas and beaches near tourist areas continue to experience problems with seawater quality (Pollution Control Department 2017b). These problems can be seen as opportunities to develop a more efficient wastewater treatment system to enable the reuse of wastewater within facilities and to reduce the amount of wastewater discharged to the sea. For example, Phuket Island, a famous tourist attraction, consumed about 70×10^6 m^3 of water annually in 2017, whereas its available water supply was 56×10^6 m^3, meaning that it only served 80% of the island's water demand (UN ESCAP 2017). As a result, in the dry season Phuket faced a severe shortage of drinking water, especially in the hotel and restaurant sectors. In 2012, Phuket had signed a BOOT concession contract for a 25,000 m^3/day wastewater reclamation project using an RO system, which was completed in 2014 and supplied reusable water via a pipeline to alleviate such shortage problems (Quantity Surveying Consultants Ltd (QSC Ltd.) 2019). Moreover, in 2021 a wastewater reclamation project collaboration was initiated between private companies investing in RO systems and renting land in the existing WWTP, on the one hand, and Phuket's local government with responsibility for inspecting the quality of reclaimed water before being transferred to communities, on the other (Karon Subdistrict Municipality 2021). Such a business model should provide an opportunity to increase investment in wastewater reclamation in other island tourism areas of the country.

Environmental protection and restoration

As communities have developed and expanded, wastewater volume has risen beyond the natural healing point, resulting in a deterioration in water quality. Therefore, the central government has issued a law to control the quality of effluents from pollution sources before it is discharged into public water sources. Thailand has several compulsory laws controlling the quality of effluents from various activities, as shown in Table 2. Regulations regarding the quality of effluents from industrial and municipal WWTPs have been in force since 1996 and 2010, respectively. In addition, since 1994, Thailand's Pollution Control Department (PCD) has set water source (including surface water, groundwater and tap water) quality standards in order to monitor, control and maintain these sources and thus ensure the health and safety of users and the conservation of natural resources and the environment. However, regulations and standards relating to the quality of reclaimed water for specific uses have not been enacted, and instead often refer to the water quality standards issued by the PCD (National Environment Board 1994). In addition, international wastewater recycling standards as mentioned in the 'Status of wastewater recycling in Thailand' section provide opportunities to adapt to local conditions, taking care not to cause any impact on the environment, society, and culture. Comparing Thailand's effluent quality criteria from WWTPs with the international benchmark of reclaimed water as shown in Table 3, it is clear that the country needs to control additional parameters (e.g., microbial and TOC parameters) in order to help reduce the risk of emerging organic pollutants and bacteria downstream. Furthermore, Thailand needs to set a monitoring framework and communication strategies to build public acceptance of reclaimed water, in accordance with international standards.

Thailand is a country with a variety of terrain and water resources, including surface water, groundwater, rivers, lakes, and seas. These all provide opportunities for developing and enforcing more stringent environmental regulations, especially with regard to wastewater recycling, which can greatly contribute to the protection and restoration of the environment. For example, limiting or reducing the amount of effluent discharged from WWTPs to public water resources by improving effluent quality and recycling in control activities will lead to compliance with effluent quality regulations. Such control activities are considered from the purpose of public water resource usage according to the Water Resources Act, BE 2018, including use by industries (such as tourism, electric power generation, and tap water supply) and any activity that uses considerable water resources causing impacts across the watershed (Thai government 2018). In addition, recycling wastewater in the tourism industry usually relies on environmental conservation for recreation, particularly on islands with drought problems (UN ESCAP 2017). This is thus another emerging driver of the reuse of treated wastewater in Thailand.

WASTEWATER REUSE CHALLENGES

Wastewater reclamation is becoming increasingly important not only in water scarce areas but also in polluted cities and environments. As a result, the practical implementation of such projects will face many challenges in the future, as shown in Table 7.

Social acceptance of wastewater reuse

In addition to technological, financial and environmental improvement, social acceptance of wastewater reclamation is a driving force behind any changes seen. Several studies have shown that social factors affect public acceptance and help determine a country's policy in terms of investment in water reuse infrastructure. For example, Garcia-Cuerva *et al.* (2016) have reported that race, education, and income level are the main factors affecting people's acceptance of reclaimed water in the United States, although their financial incentive measure influenced public acceptance and decision making for water reuse. Furthermore, Akpan *et al.* (2020) have reviewed the factors that affect public perceptions of reclaimed water in many countries, revealing that to achieve high acceptance, issues such as protection of public health, human contact, quality of reclaimed water, confidence in local authorities and technology, role of wastewater reuse in addressing water supply problems and environmental preservation, and treatment cost must be clear. The degree of public acceptance of reclaimed water being used for non-potable purposes (implying low levels of contact with humans and facilitating environmental replenishment) was higher than that of reclaimed water being used for purposes requiring direct contact with humans, such as drinking water (Massoud *et al.* 2018; Oteng-Peprah *et al.* 2018). Regional water scarcity is another factor that can accelerate

Table 7 | Main concerns regarding wastewater reclamation practices in Thailand

Concern	Comments
Framework of managing treated wastewater resources	Thailand has no legal framework for treated wastewater resources, inventory planning, quality control and protection. Wastewater resources should be integrated into the national water management plan to tackle inadequate water supply at the local level to support increased water demand in three sectors: agriculture, industry, and domestic settings.
Sustainable financial management	Financial budgets for the management of current WWTPs by local governments are insufficient. Additional costs due to wastewater reclamation facilities and O&M at the local government level need to be assessed along with the existing collection of wastewater treatment facilities for sustainable financial management. A pricing standard method regarding reclaimed water should be defined and compared to that of conventional subsidized water treatment plants.
Market for reclaimed water	Legislative provisions do not enforce the reuse of wastewater in regular situations. Hence, to expand the reclaimed water market, legal measures should be taken alongside environmental tax measures. Water users' confidence also needs to be built by stringent effluent quality standards. Social acceptance is essential for the expansion of the water reuse market, so social measures should be developed and promoted.
Proper reuse of treated wastewater	In drought situations, the reuse of effluent is widely performed in suburban areas for agriculture and aquaculture, while there are insufficient legal standards and specific guidelines for each water activity. Due to health and environmental concerns, more specific and stringent effluent standards are needed.
Quality control and monitoring of WWTPs	Effluent quality monitoring in WWTPs, at least once per month, rarely involves a real-time system, making it difficult to deal with health problems occurring from the reuse of treated wastewater. More stringent monitoring programs to increase the reliability of WWTPs are necessary to reduce the risk associated with exposure to pollutants and pathogens from treated water. Additional parameters such as emerging pollutants and microbial contaminants according to international standards should form part of water reuse planning.

water reuse. Drought may also increase public acceptance of reclaimed water as an alternative water supply (Abu-madi *et al.* 2008; Dolnicar & Schäfer 2009).

In 2013 the DEQP of Thailand conducted a survey regarding the need to reuse water in 301 participants, covering the community, agricultural and industrial sectors, reflecting society's acceptance of water reuse (Department of Environment Quality Promotion 2013). The results showed that all three sectors were already reusing water, accounting for 17, 13, and 40% of respondents, respectively, for activities not involving close human contact, such as watering plants and washing floors. The industrial sector had the highest proportion of reuse for production process activities or cooling towers, and reused water was also found to be used in toilets, firefighting, and wet scrubbers. Such results are likely due to social measures under in-house water management plans to demonstrate corporate social responsibility, which is highly encouraged in Thailand (PTT Global Chemical 2021). The DEQP also found that water reuse demand in each sector was approximately the same (44–46%), driven mainly by cost savings, water source replacement and reducing water shortages, while the drive for environmental conservation was secondary. In addition, communities' willingness to pay for treated wastewater was high (78% of relevant respondents), reflecting this sector's acceptance of water reuse. The agricultural and industrial sectors accounted for similar proportions (47–48%). Nevertheless, although many of the participants accepted reclaimed water, no reuse of water was found in activities in close contact with people, showing minimal acceptance with respect to such activities. Health and safety, treated wastewater quality in specific activities (such as food production and cultivation, including salad plants, which are sensitive to salinity and chlorine), and sufficiency of treatment technology water pipelines are other issues for which communities need greater clarity (Department of Environment Quality Promotion 2013; Akpan *et al.* 2020).

Lack of framework to manage centralized water reuse systems

Thailand is attentive to wastewater reclamation, as can be seen from the country's treated wastewater and recycling target (132 mil.m^3/yr by 2037, accounting for 3.4% of water consumption) (Office of the National Water Resources 2019). In response to this master plan, in 2017 the Wastewater Management Authority developed the Enterprise Plan for 2017–2021, focused on improving each local government's efficiency in treating wastewater and reusing at least 50% of its water consumption volume (Wastewater Management Authority 2017). However, the essential components of a wastewater recycling system, including with regard to wastewater collection (sewers and pumping stations), water sources, wastewater treatment facilities, reclaimed water storage and distribution, and water quality monitoring, were not characterized and managed throughout the system, from source water to end users. Furthermore, there is to date no legislation regarding wastewater management and the quality control of reclaimed water at the local administrative organization level, with the exception of the Municipal Wastewater Management Plan, which only states that wastewater 'fit for purpose' should be reused based on WWTPs' existing effluent quality. There is still no tangible quality goal to treat wastewater in order to satisfy the demand of different sectors, not only for agricultural and environmental flow preservation purposes, but also for reuse as drinking water.

Future community development requires the circular economy principle that wastewater should be regarded as a valuable resource from which freshwater, energy and nutrients can be extracted (Rodriguez *et al.* 2020). However, the transformation of WWTPs from being a costly service to one that is self-sustaining and that adds value to the Thai economy has yet to be considered. Moreover, wastewater reclamation should be considered as part of a national framework regarding water resource basin management that can yield more sustainable and resilient systems.

Water reuse safety

Exposure pathways and human health risks differ based on the type of treated wastewater reuse in question. Numerous studies have demonstrated the effects of pollutants and pathogens in treated wastewater when not treated with appropriate advanced technology (Lam *et al.* 2015; ISO 2018b). Therefore, the safety of water reuse is an important and challenging issue for the realization of wastewater reclamation in Thailand. When using treated wastewater, it is essential not only to protect human health and the environment but also to prevent the degradation of materials and assets throughout the system. Due to a lack of national regulatory framework for evaluating water reuse safety at the local administrative organization level, routine physical and chemical, aesthetic, microbial, and stability parameters to control the quality of reused water (ISO 2018b) have not been considered part of the monitoring criteria for WWTPs.

A promotion campaign for widespread wastewater reclamation in Thailand is ongoing according to a government plan (Office of the National Water Resources 2019), but the country has no direct regulation controlling the quality of treated wastewater for each activity. This has resulted in gaps in monitoring and quality control in community activities and may lead to long-term health and environmental risks.

Addressing this challenge often implies higher costs in improving WWTPs through advanced technology as well as in ensuring intensive water quality monitoring to minimize risks (Plumlee *et al.* 2014). To find a compromise between the additional costs of wastewater reclamation projects and human health risk, Cost–Benefit Analysis (CBA, including monetizing the health benefits) is a tool that can be used to support decision makers (Bergion *et al.* 2020). However, Thailand lacks data, and research on the health risk management of wastewater reclamation (Thepaksorn *et al.* 2016) is not yet subject to any health impact assessment (HIA) requirement by law (Department of Health 2009).

CONCLUSION

In this paper the current status and future of wastewater treatment, reclamation opportunities and challenges in Thailand have been analyzed based on national reports and a wide range of documents. The Thai government, industries, the private sector and academic institutions are increasingly paying attention to wastewater reclamation from WWTPs as a solution to the country's water scarcity problem. However, most wastewater treatment facilities here have not been upgraded or monitored for effective reuse of water. In 2018, the Thai government initiated a 20-year water resource management plan, which integrates the risk of climate change in the near future (until 2037). One national action under this plan is to expand the installation of WWTPs across the country. This presents a good opportunity to build or upgrade treatment facilities with advanced technology, in order to realize wastewater reclamation as per the needs of a growing population. However, due to a lack of national guidelines and regulations related to the design and quality control of any wastewater reclamation system for specific water reuse as well as resource recovery, individual institutions need to implement the necessary frameworks to promote sustainable and effective wastewater investments, and integrate them with this long-term WWTP installation plan. The local government organizations responsible for operating WWTPs should attend to water reuse safety, including with regard to health, the environment, and facilities, by evaluating the quality of the water reclaimed, especially in terms of microbiological constituents and emerging pollutants, to minimize risk. Monitoring criteria, tailored to the wastewater source in question and fit for specific reuses (such as landscape or agricultural irrigation, street maintenance, toilet flushing, firefighting, and construction), should be appropriately established, and regular monitoring results should be publicly disclosed to increase public confidence in the technology and the local authorities. In addition, involving the public in local government organizations' policies and regulations with regard to wastewater reclamation should be promoted in order to increase social acceptance.

Some industrial estates in Thailand have integrated wastewater reclamation in their water resource management plans to cope with both sudden and long-term droughts, as well as the use of smart system technology and water basin management approaches to increase the management efficiency of various water resources, such as tap water, reservoirs, groundwater, and wastewater recycling systems. However, water reuse by the government sector's municipal WWTPs lags behind that of the industrial sector. Thus, there are also many public–private partnership opportunities to explore and support the development of wastewater reclamation systems that can supply the reused water from municipal WWTPs for the industrial, tourism and agricultural sectors faced with water scarcity. In particular, agriculture has obtained many benefits from reusing the effluents from WWTPs, but clear regulation supporting such reuse to increase production remains lacking.

Financing wastewater treatment and reclamation facilities is a challenge across the developing world, including in Thailand. Although Thailand has already started collecting wastewater treatment fees in some provinces, it cannot cover the operation and maintenance costs involved on its own, not to mention capital investment in wastewater reclamation in the future. Therefore, investors should seek innovative financial and business models to achieve self-sustainment by adopting circular economy principles in wastewater management, leveraging not only treated wastewater but possibly also extra revenue streams such as energy, nutrient, and fertilizer recovery. This will help speed up water reuse in Thailand.

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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